RELAY COORDINATION WITH MULTIPLE BREAKER-IN / BREAKER-OUT STATIONS ON THE TRANSMISSION LINE

By

Mugdha Mayur Alverson

Gary L. Kobet
Adjunct Faculty of Electrical Engineering
(Chair)

Ahmed H. Eltom
Professor of Electrical Engineering
(Committee Member)

Abdelrahman Karrar
Associate Professor Electrical Engineering
(Committee Member)

RELAY COORDINATION WITH MULTIPLE BREAKER-IN / BREAKER-OUT

STATIONS ON THE TRANSMISSION LINE

By

Mugdha Mayur Alverson

A Thesis Submitted to the Faculty of the University of
Tennessee at Chattanooga in Partial
Fulfillment of the Requirements of the Degree of
Master of Science: Engineering

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

May 2019

ABSTRACT

The main purpose of the power system protection is to remove faults from the system as soon as possible so minimum damage happens to the transmission line or other equipment connected to the line. Tennessee Valley Authority planners want to add multiple breaker-in/breaker-out stations on a two terminal transmission lines to reduce the number of Interruptions to the customers. This paper explains how many breakers can safely be added without compromising the zone 2 time delay of 50 cycles, how to set distance relays for phase faults, instantaneous overcurrent as well as time overcurrent relays for ground fault and the difficulty associated with each. It makes recommendation for not placing the breaker-in/breaker-out stations at a certain distance on transmission line and also talks about the maximum line loadability according to NERC standard PRC-023 when zone 2 of the distance element is set higher than 130%.

DEDICATION

Sari, my Grandmother was the best woman I know. I lived with my grandmother most of my life. She did not have a good education but she made sure I got the admission to the best school and that I studied hard. What I remember the most about my grandmother is how dedicated she was to make sure we had hot, fresh, homemade food every day before we went to school and when we got home after school. She was my cheer leader all my life. She always believed in me. What I am today is because of her and so I dedicate my thesis to her unconditional love, just being there for me and taking care of me when I was little. We lost her in 2012 but I feel that her blessings are always with me.

Kyran (meaning ray of light), my miracle baby arrived in 2010. He is also a good source of inspiration and my great teacher for life lessons. He is teaching me how to be in the moment in this world when there are many distractions around me. He shows me unconditional love every day. He is so energetic and full of life that I secretly wish that he can transfer part of that energy to me. He has this ability to say the right words when his mom is under lot of pressure due to school work or at home and cheer her up. Sometimes I feel that he understands this world better than adults around me.

ACKNOWLEDGEMENTS

Gary Kobet: You are one of the best teachers I have had in my life. You are always willing to share your knowledge, always available to explain things if a student is willing to listen and curious and provide materials for the students. I am fortunate enough to come back to Chattanooga, TN and study two courses you teach at University of Tennessee at Chattanooga. It took many twist and turns along the way but I believe I have found what will make me happy in my career. Now I just have to find someone who is willing to pay me for doing the relay calculations. I will never forget the lesson you hammered during the class: “Ask questions until you understand” which is a very important lesson because not many teachers encourage this. You have this uncanny ability to come down to meet where students are and explain things in a way that is easy to understand. I am forever grateful to have you as my teacher, mentor and thesis advisor. I hope you would write a book about relays so novice like me can have one great reference book after you retire. Another lesson you taught me recently is to not be afraid to say ‘NO.’ I chose you as my thesis advisor because I knew no matter what grade I make, you would be fair to me and I would learn a lot of new things along the way. It has been a great journey through this thesis and I sure hope to see you around and keep learning from you in the next few years. Thanks for being the kindest and most available teacher to your students. I sure hope one day I pay forward the kindness you have shown me to someone else.

Dr. Eltom: You might not remember this but you said” Just do it” and here I am today finishing my M.S. Thanks for listening to my sad stories ,showing me kindness and providing encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TVA, Tennessee Valley Authority

CCPI, Customer Connection Point Interruption

LEO, Line End open

CAPE, Computer-Aided Protection Engineering

NERC, North American Electric Reliability Corporation

ATC, All Ties Closed

LIST OF SYMBOLS

$\sim$, cycles

CHAPTER 1

INTRODUCTION

1.1 Background

Tennessee Valley Authority uses a zig-zag bus arrangement or main and transfer bus switching arrangement when three or more lines are terminated at 161kV switchyards located at generating stations. The zig-zag bus arrangement provides benefits such as system stability, back up protection, and continuation of service when a bus is out of service to name a few [1].The details for the zig-zag bus are explained in the appendix A. Transmission lines are usually two terminal lines with source at each end and can have multiple tap loads along the line. There will be interruption to all the tap loads if the fault were to occur anywhere along this two terminal line. Sometimes breakers are installed at tap stations and are called "breaker-in/breaker-out" stations because there is no positive sequence source or infeed at that station. Addition of multiple breakers along the two terminal transmission lines results in interruption to fewer tap loads. Planners at TVA want to add multiple breaker-in/breaker-out stations along the transmission line to limit Customer Connection Point Interruptions (CCPI).

Chapter two covers the concept of coordination, time solution, and communication solution. Chapter three details the method to solve the problem with just one breaker on the transmission line and then apply the same method when multiple breakers are added. Chapter four discusses results and ways to make zone 2 overreach zone 1. Chapter five has the conclusion and some recommendations.

1.2 Problem Statement

Adding multiple breaker-in/breaker-out stations along the transmission line can create a relay coordination problem for protection engineers on zone distance and ground time overcurrent elements.

There could be an unacceptable time delay for zone 2 for internal fault because of the need of coordination for external faults. TVA requires this zone 2 time delay to be 50 cycles.

1.3 Objectives of the Study

The scope of this project includes: (1) how many breaker-in/breaker-out stations can be installed on a single transmission line path before the required relay coordination result in unacceptable fault clearing time (zone 2 time delay) for internal faults, (2) definition of unacceptable clearing time, and (3) what solutions would be appropriate.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Coordination

It is very important to understand the concepts of coordination, time solution and communication solution in order to solve the problem defined in chapter 1 when multiple breaker in/ breaker out stations are added to the transmission line. The thesis advisor wanted the author of this paper to also learn setting up different relays such as distance relays, instantaneous overcurrent relays, and ground time overcurrent relays at each breaker in /breaker out stations. The subject line for this project is the 161kV transmission line that connects North Knoxville TN 161kV substation to Norris Hydro Plant. For a fault anywhere along the line Norris-North Knoxville, relays at Norris and relays at North Knoxville should operate fast for this primary protection zone fault. It is impossible for the relay at Norris to distinguish if a fault near North Knox is internal or external, if the only quantities it uses are the local bus voltage and line current. The relay at Norris should operate fast if the fault is close to North Knoxville bus on line Norris to North Knoxville. The relay at Norris should delay its operation if the fault is on North Knoxville bus or beyond North Knoxville bus. For the relay at Norris, all three faults are the same because the impedance between these three fault locations is negligible; electrically they are the same point in the network. Time solution and communication solution are the two different approaches to mitigate the problem of distinguishing internal fault from external fault[2].

2.1.1 Time Solution

The primary relay at Norris operates fast for close-in faults, but delays its operation for external faults such as the faults at North-Knoxville bus or fault on the lines out of North Knoxville bus for coordination with the relays at North-Knoxville. Setting the phase or ground relays for the time solution is called coordination; this illustrates the concept of selectivity It can be achieved either using inverse time overcurrent relays or with instantaneous relays and constant (fixed or definite) time delays. The operating time of the inverse time overcurrent relays increases as the current magnitude decreases and vice versa [2].

2.1.2 Communication Solution

In a communication solution, relays at North Knoxville communicate via channel to relays at Norris whether the fault is internal (between Norris and North Knoxville line) or external (fault at North Knoxville bus or on lines out of North Knoxville) by means of directional elements which determine fault direction by comparing the phase angle of the fault current(s) relative to the a polarizing or reference quantity (e.g., faulted phase voltage(s)). Similarly, relays at Norris communicate similar information to relays at North Knoxville. If the fault is in the primary zone between the Norris to North Knoxville line, both relays at Norris and North Knoxville operate together at high speed. For external fault, relays at Norris and North Knoxville do not operate (restrain). This is called pilot relaying [2].

2.2 Bus Breakup

Bus breakup relays are placed where there is a load or generator between double breakers. The bus breakup relays provides the back up for the failure of the line relay or for failure of the breaker on the transmission line. All breakers are tripped on a bus for the bus back up. The settings for the bus back up relays and bus breakup relays are set the same[1]. The details about bus break up relay and how to set them are detailed in the appendix A.

CHAPTER 3

METHODOLOGY

3.1 Background on Zone Distance Protection for Phase Faults

Distance protection is widely used for phase faults at 69kV or higher voltage levels. Protective relays measure the electrical quantities such as voltage and current to discriminate between tolerable conditions (load) or intolerable conditions (faults). Protective relays should not operate under normal steady state condition or for maximum emergency load conditions. If a fault is present, the relay sends a trip signal to the breaker to open to minimize the damage cause by fault. The fault can be caused by winds, ice on transmission line, tree branches falling on the lines, lightning strikes or by insulation deterioration. A distance relay measures the voltage and current and hence measures apparent impedance $\frac{V}{I} = Z$. The distance relay has a fixed setting ("reach") which is set at some percentage of the line positive sequence impedance; this is the threshold value [3]. The ratio of voltage to current would be a certain value when there is no fault present on transmission line; this is called load impedance, which is larger than the threshold value and falls outside the relay operate zone. The impedance will be smaller when there is a fault on the transmission line compared to the threshold setting/reach. The distance relay will then operate and send a trip signal to the breaker to open to clear the fault[3].

3.1.1 Zone 1 and Zone 2 Reach

Zone 1 of the distance element is usually set at 80% to 90% of the total line positive sequence impedance and operates instantaneously when there is a fault present on transmission line. Zone 1 reach cannot be set to 100 % of the positive sequence line impedance because of inaccuracies in the system model (+/-10%), the instrument transformers (+/-10%), and the relay measurement accuracy (+/-5%)[2].

Zone 2 reach can be set to cover the 100% of the total line positive sequence impedance of the primary line plus 50% of the total line positive sequence impedance of the next line, but never less than 120% of the total line positive sequence impedance. Zone 2 operates with time delay. By setting the zone 2 to greater than 120% of the total line positive sequence impedance covers the 100% of the primary line and also 20% or more of the next line. This can cause relay to trip if there is a close in fault on the next line and that is why zone 2 is delayed to give primary protection at the remote end to trip first[2]. Note that every utility has their own philosophy of setting relays. For TVA, zone 1 reach is set 80-90% of the total line positive sequence impedance and zone 2 reach is set no less than 120% of the total line positive sequence impedance.

Another important factor to consider when coordinating the relays is how much of the zone 2 of one line section reaches past the next line's zone 1:

- If the zone 2 of the first line section does <u>not</u> reach past the zone 1 of the next line, the zone 2 of first line will only need to coordinate with the next line <u>zone 1</u> and its breaker failure (BF) timer (if any), plus margin (15~)

  Zone 2 timer of first line = Next line zone 1 + BF timer of next line + margin (Equation 1)

- If the zone 2 of the first line section <u>does</u> reach past the zone 1 of the next line, the zone 2 of first line will need to coordinate with the next line <u>zone 2</u> and its breaker failure (BF) timer (if any), plus margin (15~).

  Zone 2 timer of first line = Next line zone 2 + BF timer of next line + margin (Equation 2)

Note that all breaker failure timers are assumed to be 15 cycles for this project.

3.1.2 Relay Coordination with One Breaker

This can be better explained by adding the Clinton breaker on the Norris to North Knoxville line as shown in Figure 3.1. The original Norris to North Knoxville line is 22 Ω. Zone 2 of the Norris is set to 28 Ω which is the 130% of the total line positive sequence impedance. When the Clinton breaker is added on this Norris to North Knoxville line, the new line impedance is 7.7 Ω, and the new zone 2 for the Norris to Clinton line is 10 Ω (130%). The reach of this Norris zone 2 past Clinton is 2.3Ω (10 - 7.7) which is less than the zone 1 setting of Clinton to North Knoxville line (12.1 Ω). Therefore Norris zone 2 only coordinates with zone 1 of Clinton to North Knoxville plus Clinton breaker failure timer.

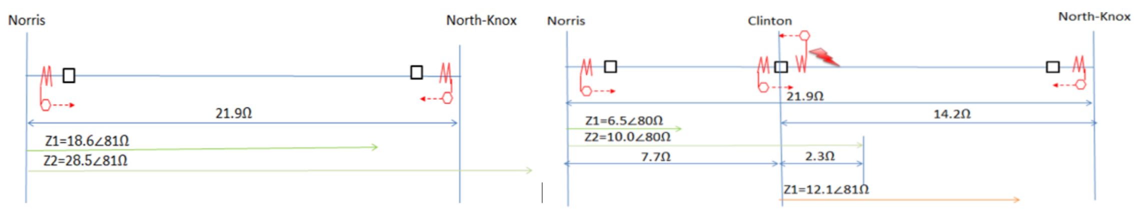

Figure 3.1 Zone Settings for the Original Line with Clinton Breaker

Total clearing time for Z1 fault on Clinton-North-Knoxville line = Clinton Z1+Clinton BF timer

$$= 1\sim + 15\sim = 16\sim$$

Norris Z2 time delay $=16\sim + 15\sim = 31\sim \cong SET\ 35\sim$.

Clinton Z2 coordinates with North-Knoxville Bus Breakup short reach is the next step in coordinating the relays.

$NorthKnoxville\ Bus\ Breakup\ operation$

$$= NorthKnoxville\ Short\ Reach\ time + LockoutRelayTime + Breaker\ Time$$

= 20+1+3=24 ~

Clinton Z2 time delay =24+15 = 39 ~ so set it to 40~.

3.2 Relay Coordination with Multiple Breakers

The same process is used in setting up relays when North Knoxville is looking toward Norris and when there are more breakers added on this transmission line.

3.2.1 Zone 1 and Zone 2 Reach, Norris Looking to North Knoxville

Figure 3.2 shows the zone 1 and zone 2 reach settings for each line section when breakers are added one at a time at Clinton, Eagle Bend, Buffalo Rd, Andersonville and Heiskell in that order. Zone 1 is set to 80% of positive sequence line impedance and zone 2 is set to 130% of the positive sequence line impedance. Note that zone 1 and zone 2 settings for each line section will be the same as shown in Figure 3.2 when North Knoxville is looking towards Norris.

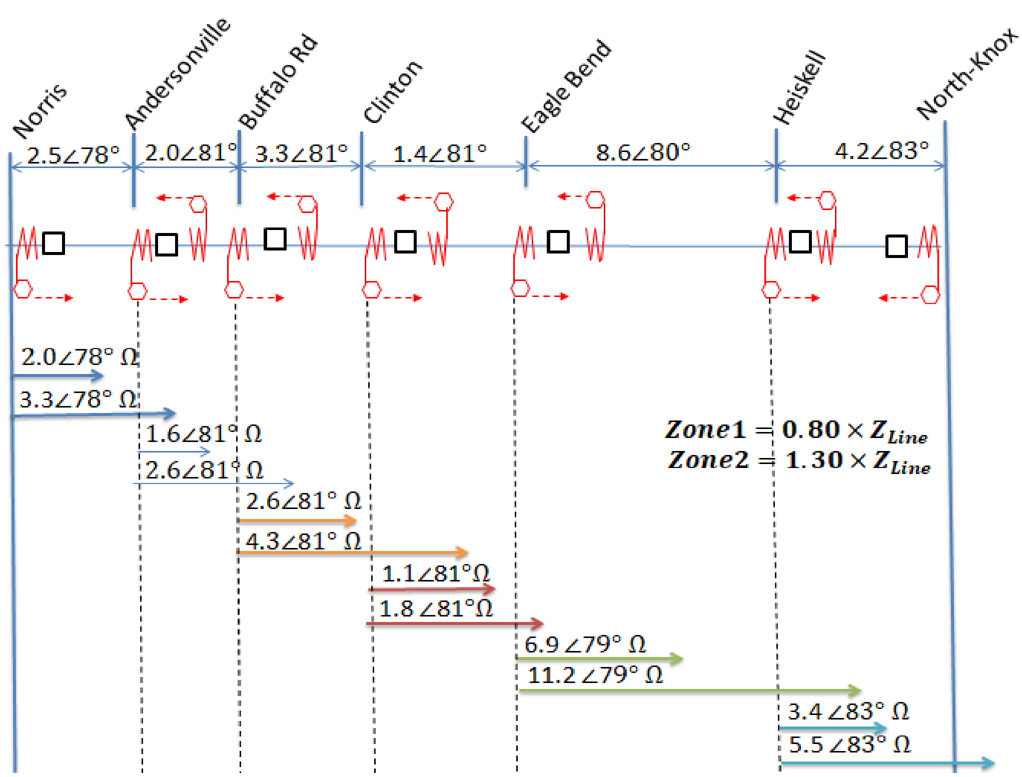

Figure 3.2 Zone 1 and Zone 2 Settings for each Line Section with Multiple Breakers on Line

3.2.2 Time Delay Setting

Figure 3.3 shows the settings of fault clearing time for zone 1 and zone 2 when breakers are added at Clinton, Eagle Bend, Buffalo Rd, Andersonville and Heiskell when Norris is looking towards North Knoxville and when North Knoxville is looking towards Norris. There is a zone 2 time delay of 65 cycles at Heiskell when North Knoxville is looking towards Norris in Figure 3.3. Pilot protection is used when zone 2 timer is longer than the required maximum zone 2 timer of 50 cycles to clear the fault.

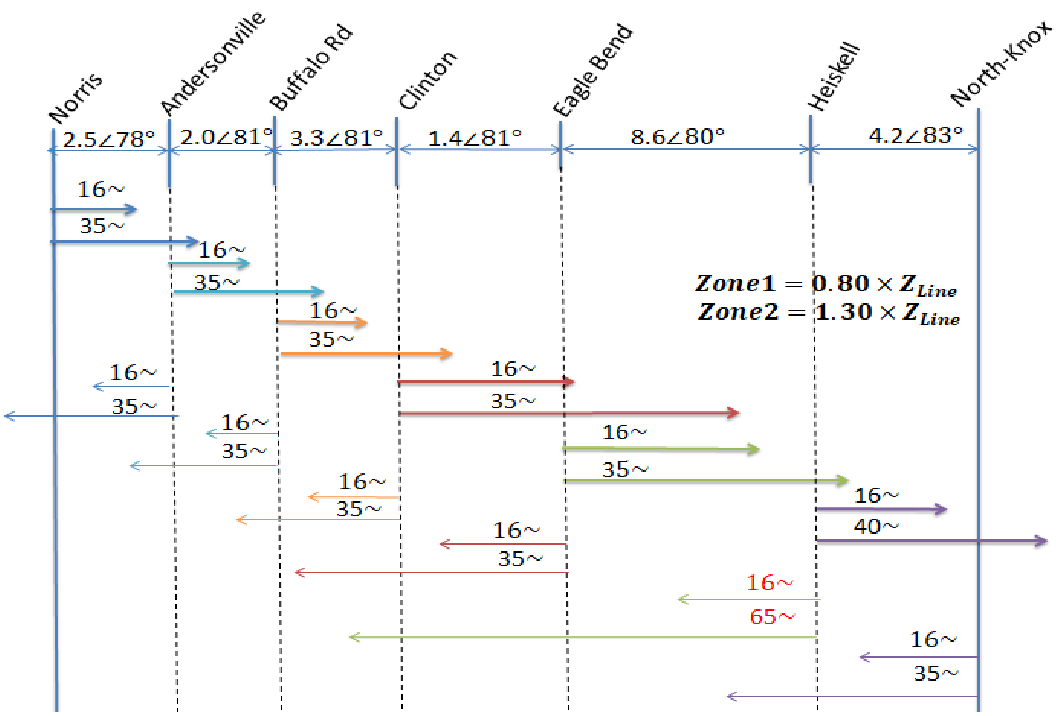

Figure 3.3 Zone 1 and Zone 2 Timer Settings with Multiple Breakers on Line

Table 3.1 summarizes the zone distance element settings when Norris is looking towards North Knoxville after multiple breakers have been added to the Norris to North Knoxville transmission line. Table 3.2 indicates the zone distance element settings when North Knoxville is looking towards Norris.

Table 3.1 Summary of Distance Element Setting_ Norris Looking towards North Knoxville

Line section	Z1= 0.80 *Zline Primary (Ω)	Z1 secondary (Ω)	Z1 fault clearing time ~	Z2= 1.3 *Zline Primary (Ω)	Z2 secondary (Ω)	Z2 fault clearing time ~
Norris to Andersonville	2.00∠78°	0.34∠78°	16	3.25∠78°	0.56∠78°	35
Andersonville to Buffalo Rd	1.60∠81°	0.27∠81°	16	2.60∠81°	0.45∠81°	35
Buffalo Rd to Clinton	2. 64∠81°	0.45∠81°	16	4.29∠81°	0.74∠81°	35
Clinton to Eagle Bend	1.12∠81°	0.19∠81°	16	1.82∠81°	0.31∠81°	35
Eagle Bend to Heiskell	6.88∠80°	1.18∠80°	16	11.18∠80°	1.92∠80°	35
Heiskell to North Knoxville	3.36 ∠83°	0.58 ∠83°	16	5.46 ∠83°	0.94∠83°	40

Table 3.2 Summary of Distance Element Setting_ North Knoxville Looking towards Norris

Line section	Z1= 0.80 *Zline Primary (Ω)	Z1 secondary (Ω)	Z1 fault clearing time ~	Z2= 1.3 *Zline Primary (Ω)	Z2 secondary (Ω)	Z2 fault clearing time ~
Andersonville to Norris	2.00∠78°	0.34∠78°	16	3.25∠78°	0.56∠78°	35
Buffalo Rd to Andersonville	1.60∠81°	0.27∠81°	16	2.60∠81°	0.45∠81°	35
Clinton to Buffalo Rd	2. 64∠81°	0.45∠81°	16	4.29∠81°	0.74∠81°	35
Eagle Bend to Clinton	1.12∠81°	0.19∠81°	16	1.82∠81°	0.31∠81°	35
Heiskell to Eagle Bend	6.88∠80°	1.18∠80°	16	11.18∠80°	1.92∠80°	65
North Knoxville to Heiskell	3.36 ∠83°	0.58 ∠83°	16	5.46 ∠83°	0.94∠83°	35

The zone 2 time delay of Heiskell to Eagle Bend (11.18 Ω) overreaches the zone 1 of Eagle Bend to Clinton when North Knoxville is looking towards Norris. Therefore Heiskell to Eagle Bend has the zone 2 fault clearing time of 65~ in Table 3.2. When zone 2 is set to 120% of the positive sequence line impedance instead of 130%, Heiskell to Eagle Bend tap also has zone 2 fault clearing time of 65~.

Equations 2 and 3 were used to calculate the zone 2 time delay and detailed information on this calculation is available in appendix A.

3.3 NERC Standard PRC-023 and Loadability of Distance Relays

NERC standard PRC-023, Transmission Relay Loadability, was established to ensure that bulk electric power utilities follow three criteria: (1) protective relays should not limit transmission line loadability; (2) operators can make changes that will not jeopardize the reliability of the system; and (3) detect all faults and protect the power systems. According to PRC-023, phase relay settings should meet at least one of the many criteria outlined for it to be not a limiting factor for transmission loading [2, 4] and also require that phase relay settings provide reliable operation of the relays in their protection zones for all phase faults. The following steps should be taken if the settings of the phase relays do not meet any of the criteria listed above. Step 1 is to use the phase relay with different characteristics that will detect all the faults and meet at least one of the many criteria. Step 2 is to treat “the load limitation imposed by the relay per PRC-023 [2]” as the loadability limit of the utility. If step 2 is taken than the phase relay should be set 125% of the line impedance with the highest angle setting available for that relay (up to 90°) according to Requirement 1.

PRC-023 requirement 1, Criteria 1 indicates that loadability should be evaluated at 85% voltage, at 30 degree power factor angle and transmission line should not operate at or below 150% of line’s seasonal 4 hour rating or the available rating that is closest to 4 hours. The 150% factor is for safety and ensures the relay does not trip on short term overload. The transmission line loadability is calculated using the equation 3.

$$I_{LL} = \frac{0.85 * V_{L-L}}{\sqrt{3} * 1.5 * Z_{relay30}} \qquad \text{(Equation 3)}$$

where

I_{LL} is the load limit of the relay setting

V_{L-L} is the phase to phase rated voltage at the relay location

$Z_{relay\ 30}$ is the impedance measured from the origin to the relay's operating characteristic at a 30° angle [2]

3.3.1 Line Loading Calculations

The upper limit for Zone 2 reach is the reach that will not trip on 150% maximum emergency line loading in MVA. Maximum emergency line loading is provided by transmission planning department at TVA. Maximum emergency line loading values are in MVA and given for 1 hour or 4 hour ratings and are also temperature based. For the relay coordination, 4 hour at 32°F (winter) values are used for maximum line loading calculation as shown in Table 3.3 along with the calculated data for this project.

Table 3.3 Phase Relay Settings and Transmission Relay Loadability

	Zline	Z1= 0.80*Zline	Z2 =1.3*Zline	Z1R@MTA	Z2R@MTA	Z2R@30°	I @30°, kA	Calculated Line rating MVA, 30°	Maximum Emergency Loading 4 hr, 32° F, MVA	% Margin= (calculated Line Rating/given line Rating)*100
Norris to Andersonville	2.5	2.00	3.25	2.00	3.25	2.30	22.89	6382.86	227.3	2808
Andersonville to Buffalo Rd	2.0	1.60	2.60	1.60	2.60	1.84	28.61	7978.58	281.1	2838
Buffalo Rd to Clinton	3.3	2.64	4.29	2.64	4.30	3.04	17.34	4835.50	398.5	1213
Clinton to Eagle Bend Tap	1.4	1.12	1.82	1.12	1.82	1.29	40.87	11397.97	398.5	2860
Eagle Bend Tap to Heiskell	8.6	6.88	11.18	6.89	11.20	7.92	6.65	1855.48	281.1	660
Heiskell to North Knoxville	4.2	3.36	5.46	3.36	5.47	3.87	13.62	3799.32	281.1	1352

A 161kV Norris to Andersonville line has an impedance of 2.5∠78°Ω. Zone 1 reach is set to 80% of the line impedance and therefore it is 2.00∠78°Ω. Zone 2 is set 130% of the line impedance and therefore it is 3.25∠78°Ω. Equation 4 describes the various points on mho circle.

$$Z_x = Z_R \cos(\Phi_R - \Phi_x) \qquad \text{(Equation 4)}$$

where

Z_x is the impedance from the origin at any point on the circle at angle Φ_x

Z_R is the relay reach at Φ_R [2]

Now the reach of the distance relay is evaluated at maximum torque angle setting of 75°.

$$Zone1_{MTA} = \frac{Zone1_{@78}}{COS(MTA-78)} = \frac{2.00}{COS(75-78)} = 2.0\ \Omega\text{primary} \qquad \text{(Equation 5)}$$

Similarly,

$$Zone2_{MTA} = \frac{Zone2_{@78}}{COS(MTA-78)} = \frac{3.25}{COS(75-78)} = 3.25\ \Omega\text{primary} \qquad \text{(Equation 6)}$$

According to the PRC-023, requirement 1, Criteria1, zone 2 reach at 30° is evaluated using equation 7 and then line loadability is calculated using equation 3.

$$Zone2_{30} = (Zone2_{MTA}) \star \left(cos(MTA - 30°)\right) \qquad \text{(Equation 7)}$$

$$Zone2_{30} = (3.25) \star \left(cos(75 - 30°)\right) = 2.30\Omega\text{primary.}$$

$$I_{LL} = \frac{0.85*161000}{\sqrt{3}*1.5*2.30} = 22.90\ kAprimary$$

The next step is to calculate the line loadability in MVA since TVA line loadability ratings are in MVA as shown in Equation 8.

$$S = \sqrt{3}VI = \sqrt{3}(161kV)(22.90kA) = 6383\ MVA \qquad \text{(Equation 8)}$$

The maximum emergency line loadability rating at 4 hour, 32°F for Norris to Andersonville line is 227 MVA. Since the 4 hour rating for this line is less than 6383 MVA, the setting meets the requirements of Criteria 1. Same method is used to calculate the line loading of the other lines as new breakers are added on line.

3.4 Residual Ground Time Overcurrent Relay for Ground Fault Protection

Instantaneous overcurrent relay (50N) and residual ground time overcurrent relay (51N) are used together for ground fault protection. All-ties-closed source impedances for Norris and North Knoxville are used to calculate 51N settings. Ground fault current, 3I0, is calculated by applying a single phase to ground fault at the remote end terminal. For Norris to North Knoxville line without any breakers in between, the ground fault current is measured from the relay at Norris while applying single phase to ground fault at North Knoxville terminal. The positive, negative and zero sequence networks are connected in series to find the total 3I0 fault current and then the 3I0 current in relay is obtained. The 51N (residual ground time overcurrent) pickup is calculated by taking the 10 percent of the 3I0 through relay and then dividing by CT ratio (240:1) to get the secondary value. By setting 51N pick up to 10% of the all ties closed remote bus ground fault, it provides sensitivity (1000%) for a resistive ground fault such as trees. Relay will be set using this secondary value of 3I0. Schweitzer very inverse time overcurrent relay equation is used to calculate time dial or time lever as shown in equation 9. The very inverse time overcurrent characteristic indicates that the operation of the device is inversely proportional to fault current. If the fault current is high, the relay will operate slowly and vice versa.

$$T_P = T_D\left(0.0963 + \frac{3.88}{M^2-1}\right) * 60 \qquad \text{(Equation 9)}$$

where

Tp = operating time of the relay

TD= Time dial

M= $\frac{3I0\ fault\ current}{pick\ up\ current}$

M in the equation 9 represents the ratio of the 3I0 fault current through relay to pick up. The operating time Tp is obtained from the Figure 3.3. Table 3.4 shows the summary of settings for 51N, Norris looking towards North Knoxville, when a single phase to ground fault was applied at the North Knoxville bus and compared with the CAPE data provided by the instructor. Table 3.5 shows the settings for 51N when North Knoxville is looking towards Norris. A sample calculation for total 3I0, relay 3I0, TD is attached in the appendix A. There is a difference in CAPE data and hand calculation data because CAPE takes into account for zero sequence mutual coupling which hand calculation does not due to complexity of the problem.

3.4.1 51N Settings, Norris Looking towards North Knoxville

Table 3.4 Summary of 51N Settings Norris Looking to North Knoxville

Location		Calculated Primary (Amps)		Calculated Secondary (Amps)		Cape Primary (Amps)		%Error in Total 3I0 =	%Error in Relay 3I0 =	TD
Relay @	Ground Fault @	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	Time dial
Norris	Clinton	7205	3970	30	17	7425	4146	2.96	4.25	4.3
Clinton	North Knoxville	27782	1371	116	6	27136	1067	2.38	28.49	4.9
Clinton	Eagle Bend	7144	3640	30	15	7355	3780	2.87	3.70	4.3
Norris	Buffalo Rd	7821	5093	33	21	8112	5400	3.59	5.69	4.3
Norris	Andersonville	8621	6117	36	25	9012	6562	4.34	6.78	4.3
Eagle Bend	Heiskell	11010	2061	46	9	11494	2002	4.21	2.95	4.3

There is a high percentage of error when CAPE 3I0 current values from relay were compared with that of the hand calculated values in an example where the relay is located at Clinton and a single phase to ground fault is applied at North Knoxville. This is due to the zero sequence mutual impedance. For North Knoxville bus fault, other lines with high currents that are terminated at North Knoxville are mutually coupled with the Heiskell North Knoxville line, so the effect of the zero sequence mutual impedance is higher. For faults towards Norris, currents in those other lines terminated at North Knoxville are lower and therefore the effect of the zero sequence mutual impedance coupling is less.

3.4.2 51N Settings, North Knoxville Looking towards Norris

Table 3.5 Summary of 51N Settings North Knoxville looking to Norris

Location		Calculated Primary (Amps)		Calculated Secondary (Amps)		Cape Primary (Amps)		%Error in Total 3I0 =	%Error in Relay 3I0 =	TD
Relay @	Ground Fault @	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	Time dial
Clinton	Norris	10513	2260	44	9	10296	2156	2.11	4.82	4.3
North Knoxville	Clinton	7205	3235	30	13	7425	3279	2.96	1.34	4.3
North Knoxville	EagleBend	7144	3504	30	15	7355	3575	2.87	1.99	4.3
Clinton	Buffalo Rd	7821	2729	33	11	8112	2712	3.59	0.63	4.3
BuffaloRd	Andersonville	8621	2505	36	10	9012	2451	4.34	2.20	4.3
North Knoxville	Heiskell	11010	8950	46	37	11494	9493	4.21	5.72	4.3

3.5 Schweitzer Time Overcurrent Relay

Schweitzer time overcurrent relay has many characteristic curves such as U.S. very inverse, inverse, U.S. moderately inverse, U.S. extreme inverse, U.S. short time inverse, I.E.C inverse, I.E.C very inverse, I.E.C extremely inverse, I.E.C Long-term inverse and I.E.C short term inverse which are shown in Figure 3.4. Schweitzer very inverse time overcurrent relay curve is chosen for this project.

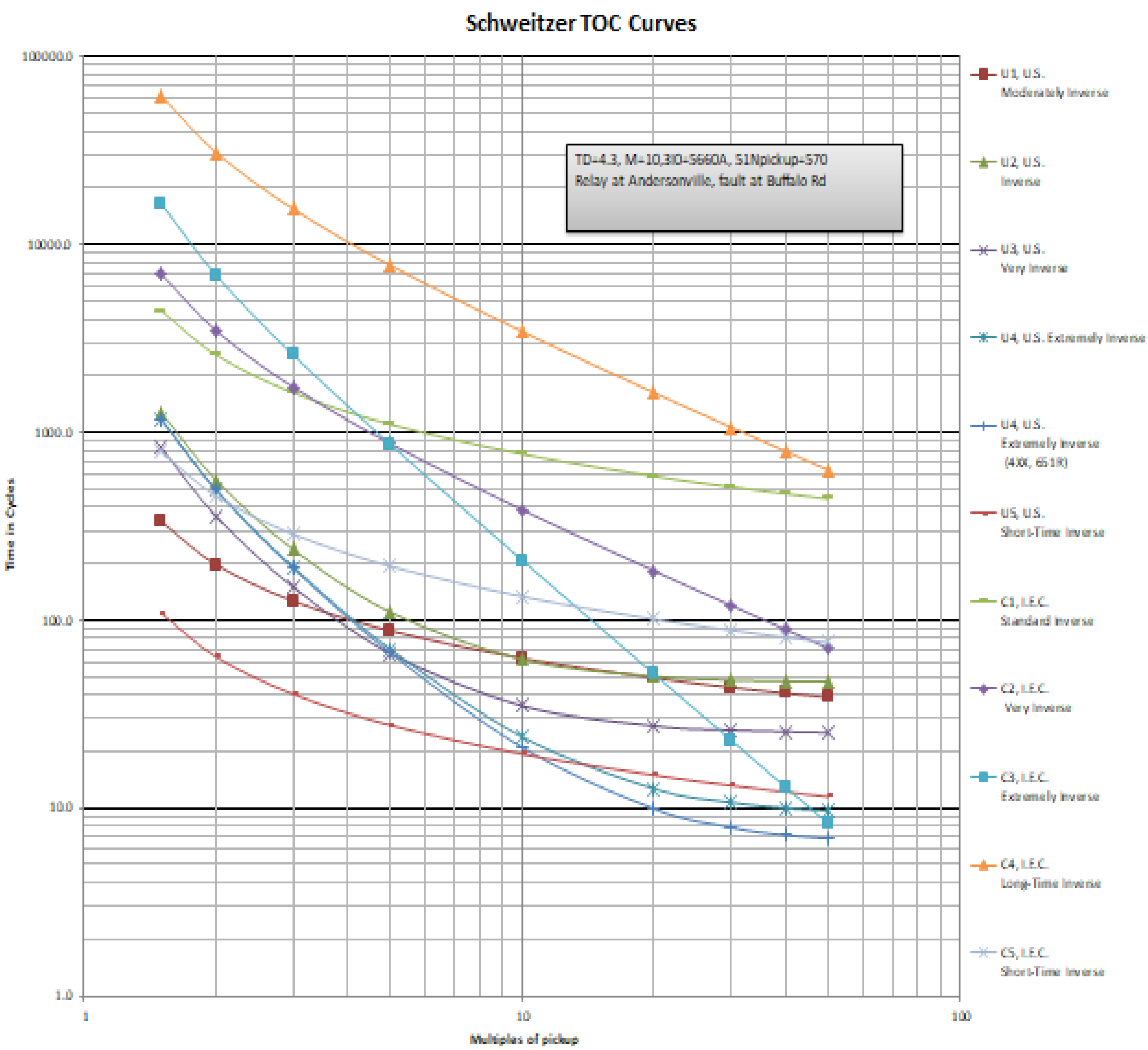

Figure 3.4 Relay Operating Time in Cycles vs Multiples of Pickup

3.6 Operating Time vs Fault Current with Multiple Breakers

Table 3.6 is used to plot the operating time (Tp in cycles) vs. 3I0 (current in primary) as shown in Figure 3.5.

Table 3.6 Relay Operating Time and 3I0 Fault Current Calculation Summary

	3I0 Norris fault@ Andersonville T_D=4.3		3I0 Andersonville fault@Buffalo Rd TD=4.3		3I0 from Buffalo Rd Fault @ Clinton TD=4.3		3I0 from Clinton Fault @ EagleBend TD=4.3		3I0 from EagleBend Fault @ Heiskell TD=4.3		Heiskell fault@ NorthKnoxville T_D=4.9	
	PU=690	3I0= 6920Ap	PU=570	3I0= 5660	PU=430	3I0= 4330	PU=290	3I0= 2920	PU=220	3I0= 2170	PU=140	3I0= 1420Ap
M	Tp(cycles)	I(Ampsprimary)	Tp(cycles)	I(Ampsprimary	Tp(cycles)	I(Ampsprimary)	Tp(cycles)	I(Ampsprimary)	Tp(cycles)	I(Ampsprimary)	Tp(cycles)	I(Ampsprimary)
1.5	825.7	1035	825.7	855	825.7	645	825.7	435	825.7	330	940.9	210
2	358.5	1380	358.5	1140	358.5	860	358.5	580	358.5	440	408.6	280
3	150	2070	150	1710	150	1290	150	870	150	660	170.9	420
5	66.6	3450	66.6	2850	66.6	2150	66.6	1450	66.6	1100	75.8	700
10	35	6900	35	5700	35	4300	35	2900	35	2200	39.8	1400
20	27.4	13800	27.4	11400	27.4	8600	27.4	5800	27.4	4400	31.2	2800
30	26	20700	26	17100	26	12900	26	8700	26	6600	29.6	4200
40	25.5	27600	25.5	22800	25.5	17200	25.5	11000	25.5	8800	29	5600
50	25.2	34500	25.2	28500	25.2	21500	25.2	14500	25.2	11000	28.8	7000

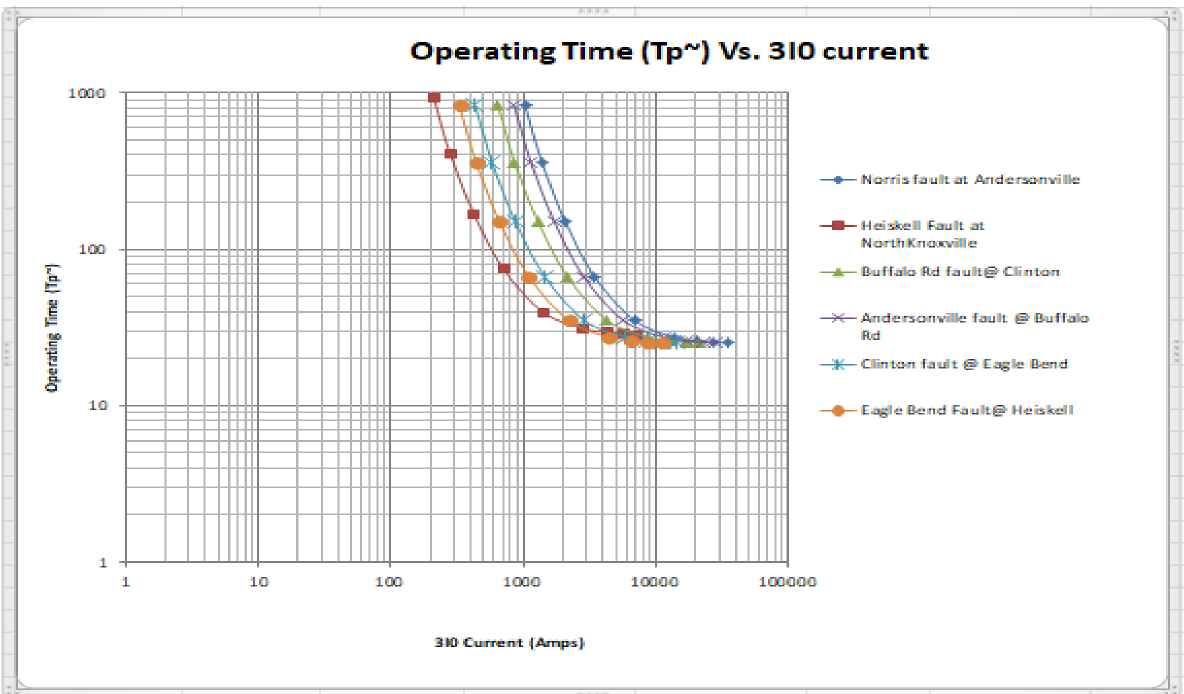

Figure 3.5 Operating Time vs. 3I0 Current using Very Inverse Relay

3.7 Instantaneous Overcurrent Element Settings for Ground Fault Protection

Setting of an instantaneous overcurrent relay, 50N, requires measuring maximum 3I0 from the local terminal when a single phase to ground fault is applied at remote end. The pick-up value of 50N is then set to 130% of the 3I0 from the relay. The instantaneous overcurrent element is an under reaching element just like zone 1 distance element. Since zone 1 is an under reaching element, it cannot discriminate whether the fault is at the end of the line or at the remote bus in a non-pilot settings. By raising the pick-up value of 50N, it acts as an under reaching element. The fault has to be closer to the relay terminal before the relay will operate. The Instructor considered machine subtransient impedances (Xd") and a 1.05 p.u flat voltage profile as the worst-case to produce higher fault currents using CAPE program and provided the source impedances at both terminal using following methods. Directional overcurrent relay (67N) should be used instead of Instantaneous over current relay (50N).

3.7.1 50N Settings, Norris Looking towards North Knoxville

All-ties-closed source impedances for Norris and the n-1 source impedance for North Knoxville are used for setting the 50N element when Norris is looking toward North Knox. In order to get the maximum 3I0 contribution from local terminal (Norris), a single phase to ground fault is applied at North Knoxville terminal while taking out one line at a time from North Knoxville bus and checking for 3I0 current contribution at Norris. This process gives the source impedance for North Knoxville. All ties closed meaning all lines (Bull Run and Clinton, Pineville and Volunteer on Bus 1 and Bus 2) at Norris terminal are connected in the system. Using CAPE program, Norris gets maximum 3I0 when Bull Run – NorthKnox #1 was out and source impedances are as shown below.

Norris ATC: Z+ = 0.00411 + j0.02679 p.u, Z0 = 0.01436 + j0.07506 p.u

North Knox n-1: Z+ = 0.00137 + j0.01414 p.u, Z0 = 0.00320 + j0.01937 p.u (with Bull Run-North Knox #1 out)

Norris to North Knoxville line was also out while calculating the two source impedances shown above. Table 3.7 shows the summary of the settings for 50N, instantaneous overcurrent element when Norris is looking towards North Knoxville.

Table 3.7 Norris Looking towards North Knoxville_50N settings

Location		Calculated Primary (Amps)		CAPE Primary (Amps)		%Error in Total 3I0 =	%Error in Relay 3I0 =	50N_pickup Primary (Amps)	50N_pickup Secondary (Amps)
Relay @	Ground Fault @	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*10$	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	1.3*Relay 3I0	(1.3*Relay 3I0)/240
Norris	Clinton	7146	3956	7468	4254	4.31	7.01	5040	21
Clinton	North Knoxville	24592	1350	24900	1254	1.24	7.66	1680	7
Clinton	Eagle Bend	7075	3620	7372	3879	4.03	6.68	4800	20
Norris	Buffalo Rd	7779	5080	8214	5541	5.30	8.32	6720	28
Norris	Andersonville	8586	6110	9159	6734	6.26	9.27	7920	33
Eagle Bend	Heiskell	10610	2040	10856	2109	2.27	3.27	2640	11
Norris	North Knox	24592	1350	24900	1254	1.24	7.66	1680	7

3.7.2 50N Settings, North Knoxville Looking towards Norris

All-ties-closed source impedance for North Knoxville and the n-1 source impedance for Norris are used for setting the 50N element when North Knoxville is looking toward Norris. In order to get maximum 3I0 contribution from North Knoxville, a single phase to ground fault is applied at Norris while taking out one line at a time from Norris terminal and 3I0 is measured at North Knoxville. This process gives the source impedance for Norris. North Knoxville gets maximum 3I0 when Norris-Hinds Valley-Volunteer line is out. The source impedances for North Knoxville terminal are as shown below.

North Knox ATC: Z+ = 0.00110 + j0.01219 p.u, Z0 = 0.00287 + j0.01731 p.u

Norris n-1: Z+ = 0.00630 + j0.04166 p.u, Z0 = 0.01746 + j0.11679 p.u (with Norris-Hinds Valley-Volunteer out)

Norris to North Knoxville line was also out while calculating these two source impedances shown above. Table 3.8 shows the summary of the settings for 50N, instantaneous overcurrent element when North Knoxville is looking towards Norris.

Table 3.8 North Knoxville Looking towards Norris _50N settings

Location		Calculated Primary (Amps)		CAPE Primary (Amps)		%Error in Total 3I0 =	%Error in Relay 3I0 =	50N_pickup Primary (Amps)	50N_pickup Secondary (Amps)
Relay @	Ground Fault @	Total 3I0	Relay 3I0	Total 3I0	Relay 3I0	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	$\left\lvert\frac{Calculated-Cape}{Cape}\right\rvert*100$	1.3*Relay 3I0	(1.3*Relay 3I0)/240
Clinton	Norris	7588	2258	7855	2388	3.40	5.44	2880	12
North Knoxville	Clinton	6387	3236	6679	3459	4.37	6.45	4320	18
North Knoxville	EagleBend	6446	3500	6758	3757	4.62	6.84	4560	19
Clinton	Buffalo Rd	6543	2729	6808	2902	3.89	5.96	3600	15
BuffaloRd	Andersonville	6858	2503	7119	2655	3.67	5.73	3360	14
North Knoxville	Heiskell	10714	8920	11567	9794	7.37	8.92	11520	48
North Knoxville	Norris	7588	2258	7855	2388	3.40	5.44	2880	12

CHAPTER 4

RESULTS AND DISCUSSION

A zone 2 time delay was within the TVA required limit of 50 cycles until breaker-in/breaker-out station was added at Heiskell. Figure 3.3 shows the zone 2 time delays of 65 cycles at Heiskell when North Knoxville is looking towards Norris. The author of this paper has come up with couple other ways to show zone 2 overreaching zone 1 in section 4.1 and 4.2.

4.1 Zone 2 Overreaching Zone1 with 140 to 150% of Positive Sequence Line Impedance

The next step was to figure out a way to make zone 2 of one line section overreach next line zone 1. By setting zone 2 to 140% of the positive sequence line impedance caused Eagle Bend Z2 reach past zone 1 setting of Heiskell (3.36Ω) as shown in Table 4.1. Therefore zone 2 of Eagle Bend coordinates with Heiskell zone 2 timer plus Heiskell BF timer and margin of 15∼. This makes zone 2 time delay for Eagle Bend to be 70∼. The same is true for the line section of Buffalo Road to Clinton. The zone 2 setting for Buffalo Rd-Clinton overreaches zone 1 of Clinton to Eagle Bend. Therefore zone 2 time delay of Buffalo Rd is set to 65∼. The detailed calculation for this setting is explained in appendix A.

Table 4.1 Zone 2 Overreaches Zone 1

	Zline	Zone1 =0.80*Zline	Zone2 = 1.4*Zline	Z2-Zline	(Z2-Zline)<nextZ1?
Norris to Andersonville	2.5	2.00	3.50	1.00	
Andersonville to Buffalo Rd	2	1.60	2.80	0.80	TRUE
Buffalo Rd to Clinton	3.3	2.64	4.62	1.32	TRUE
Clinton to EagleBend	1.4	1.12	1.96	0.56	FALSE
EagleBend to Heiskell	8.6	6.88	12.04	3.44	TRUE
Heiskell to North-Knox	4.2	3.36	5.88	1.68	FALSE

	Zline	Zone1 =0.80*Zline	Zone2 = 1.5*Zline	Z2-Zline	(Z2-Zline)<nextZ1?
Norris to Andersonville	2.5	2.00	3.75	1.25	
Andersonville to Buffalo Rd	2	1.60	3.00	1.00	TRUE
Buffalo Rd to Clinton	3.3	2.64	4.95	1.65	TRUE
Clinton to EagleBend	1.4	1.12	2.10	0.70	FALSE
EagleBend to Heiskell	8.6	6.88	12.90	4.30	TRUE
Heiskell to North-Knox	4.2	3.36	6.30	2.10	FALSE

When setting up zone 2 at higher percentage such as 140 or 150, one should be cautious to make sure the relay will not operate for maximum emergency load conditions. Table 4.2 indicates the summary of the various scenarios where zone 2 of one line section overreaches the next line section if Norris is looking towards North Knoxville or North Knoxville is looking towards Norris.

Table 4.2 Different Scenarios where Zone2 overreach Zone 1

% of Zone 2	Which way are you looking?	Zone	Zline	Zone1	Zone2	Zone2-Zline	(Zone2-Zline) <next Z1?
140	Norris to North-Knox	Spider1 to Andersonville	0.83	0.66	1.16	0.33	FALSE
140	Norris to North-Knox	Spider3 to Clinton	1.10	0.88	1.54	0.44	FALSE
140	Norris to North-Knox	Spider6 to North-Knox	1.40	1.12	1.96	0.56	FALSE
150	Norris to North-Knox	Spider1 to Andersonville	0.83	0.66	1.25	0.42	FALSE
150	Norris to North-Knox	Spider2 to Buffalo Rd	0.67	0.54	1.01	0.34	FALSE
150	Norris to North-Knox	Spider3 to Clinton	1.10	0.88	1.65	0.55	FALSE
150	Norris to North-Knox	Spider4 to Eagle Bend	0.47	0.38	0.71	0.24	FALSE
150	Norris to North-Knox	Spider5 to Heiskell	2.87	2.30	4.31	1.44	FALSE
150	Norris to North-Knox	Spider 6 to North-Knox	1.40	1.12	2.10	0.70	FALSE

% of Zone 2	Which way are you looking?	Zone	Zline	Zone1	Zone2	Zone2-Zline	(Zone2-Zline) <next Z1?
120	North-Knox to Norris	EagleBend to Spider5	5.73	4.58	6.88	1.15	FALSE
130	North-Knox to Norris	Buffalo Rd to Spider 3	2.20	1.76	2.86	0.66	FALSE
130	North-Knox to Norris	EagleBend to Spider5	5.73	4.58	7.45	1.72	FALSE
140	North-Knox to Norris	Buffalo Rd to Spider 3	2.20	1.76	3.08	0.88	FALSE
140	North-Knox to Norris	EagleBend to Spider5	5.73	4.58	8.02	2.29	FALSE
150	North-Knox to Norris	Andersonville to Spider 2	1.33	1.06	2.00	0.67	FALSE
150	North-Knox to Norris	Buffalo Rd to Spider 3	2.20	1.76	3.30	1.10	FALSE
150	North-Knox to Norris	EagleBend to Spider5	5.73	4.58	8.60	2.87	FALSE

4.2 Zone 2 Overreaching Zone1 with Multiple Breakers

Figure 4.1 is a bit of an extreme example that shows multiple areas where zone 2 overreaches zone 1. For this example multiple breakers (Spider 1,2,3,4,5 and 6) are added at two thirds of the each line section between Norris to Andersonville, Andersonville and Buffalo Road, Buffalo Road and Clinton, Clinton and Eagle Bend, Eagle Bend and Heiskell, and Heiskell and North Knoxville.

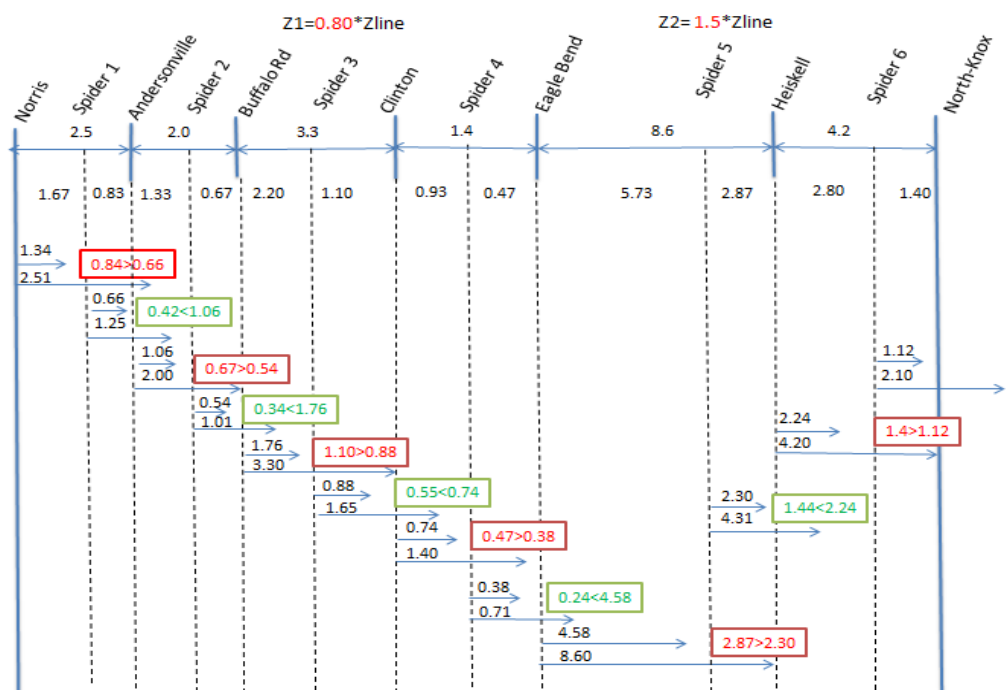

Figure 4.1 Addition of Breaker in between Each Line Section

This example also points out that it can get difficult to set up phase distance relay with the required time delay (TVA requirement of 50 cycles) as shown in Figure 4.2.

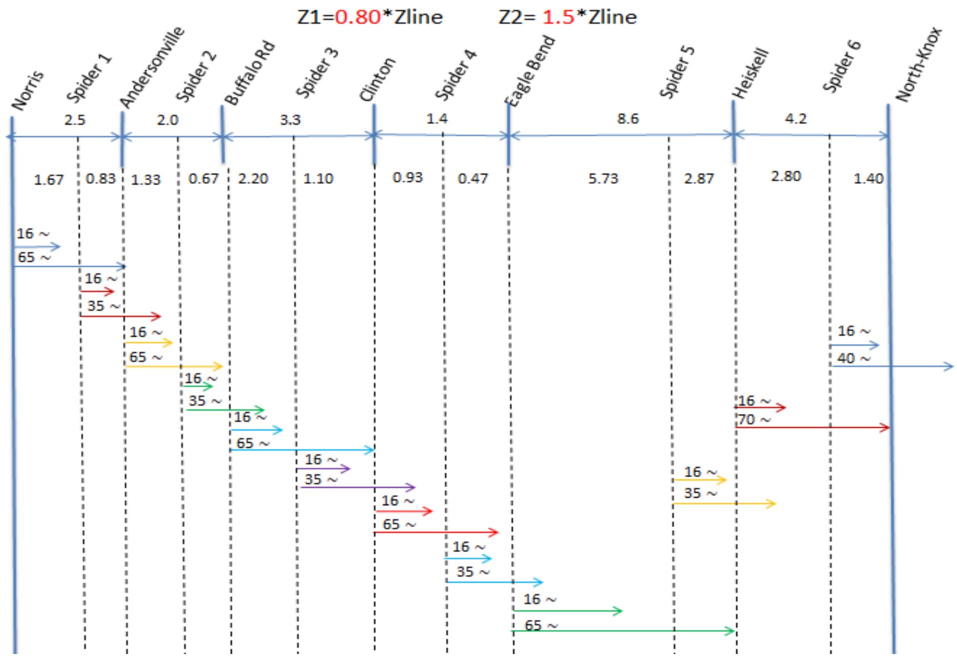

Figure 4.2 Unacceptable Zone 2 Time Delay in Multiple Line Sections

Now consider another example shown in Figure 4.3.

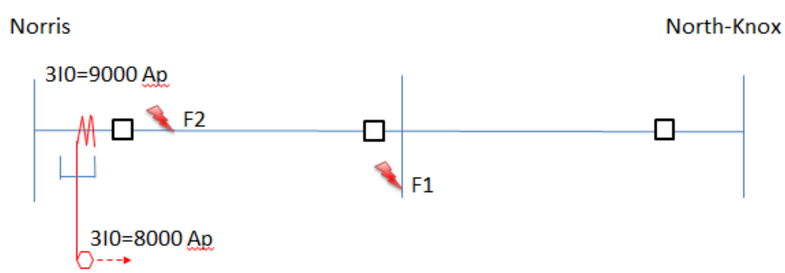

Figure 4.3 Example of Relay Settings that will not Work for Close-in Fault

If you get 8000Aprimary as 3I0 max for fault F1 from Norris relay, then the 50N or 67N settings at Norris relay will be 10400Ap (130% of 8000Ap). Now if you have a close in fault F2 where you get 9000Ap fault current, the relay at Norris will not trip because the 9000Ap fault current is less than the relay pick up setting. Pilot protection is used for this kind of situation because all the internal faults will be cleared by time delayed elements which should have been cleared by the instantaneous elements.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The addition of five breakers at Clinton, Eagle Bend, Buffalo Rd, Andersonville and Heiskell did cause zone 2 of Heiskell (11.18 Ω Ω and Heiskell Z2 past Eagle Bend =11.18 Ω -8.6 Ω=2.58 Ω) to overreach the zone 1(1.12 Ω) of Eagle Bend to Clinton line section when North Knoxville is looking towards Norris. By adding multiple breakers such as Spider 1, Spider 2, Spider 3, Spider 4, Spider 5 and Spider 6 caused the zone 2 to overreach zone 1 at six different places. If zone 2 time delay limit was to be 50∼, zone 2 time delay would have been higher than the limit at 6 different places where Spider 1 to Spider 6 breakers were added. This exercise shows how complex a problem of setting up the distance element can become when breakers are placed at certain distance from each other since impedance of the line is proportional to line length. Zone 2 is an overreaching element which detects the fault external to the primary transmission line protection zone and also trip for the internal fault beyond the zone 1 reach. If zone 2 is set to 120% of the positive sequence line impedance, the relay will protect the 100% of the primary transmission line zone and 20% of the next line zone. Zone 2 time delay must be set (i.e. trip slower) so that it gives the primary protection of the next line enough time to trip for its zone 1 fault.

5.2 RECOMMENDATIONS

The author of this paper has noticed three things: (1) when one line section is considerably longer than the next line section, it is possible for zone 2 to overreach zone 1 even when zone 2 is set at lower percentage such as 120% or 130 %. I would not recommend placing a breaker at 2/3 of each line section after these five breakers (Andersonville, Buffalo Rd, Clinton, Eagle Bend Tap and Heiskell) have been added as shown by the examples in Figures 4.1 and 4.2. (2) Precaution should be taken to make sure the relay should not operate for maximum emergency load conditions when setting up zone 2 at higher percentage such as 140% or 150% of the total line positive sequence impedance. (3) In order to get maximum contribution from the local terminal while setting a ground instantaneous element-50N, local terminal will have minimum source impedance behind the local terminal (all ties closed) and the n-1 source impedance at the remote terminal.

Pilot protection where different communication schemes can be used to detect the phase and ground fault with high speed and hence make the zone 2 time delay can essentially be instantaneous if the local and remote terminals are determining whether the fault is internal or external. Directional comparison blocking (DCB) and permissive overreaching transfer trip (POTT) are two pilot schemes that are used with phase distance relays.

REFERENCES

[1] T. E. Hundley and L. A. McKenzie, "Protective relaying applied to zig-zag bus schemes," in *Conference on Protective Relaying*, Georgia Institute of Technology, Atlanta, GA, 1963.

[2] J. L. Blackburn and T. J. Domin, *Protective relaying principles and applications*, 4 ed. Boca Raton, FL: CRC Press, 2014.

[3] R. Leelaruji and L. Vanfrett, "Power system protective relaying: basic concepts, industrial-grade devices, and communication mechanisms," KTH Royal Institute of Technology, Stockholm, Smarts-Lab-2011-003, July 2011. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:464427/fulltext01.pdf

[4] North American Electric Reliability Corporation. "Transmission relay loadability." https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-023-3.pdf (accessed 1/2/2019.

APPENDIX A

SYTEM DATA AND CALCULATIONS

Z- Bus scheme

There is a load or generation connected between the two main buses through breaker at each bus. This makes letter z and hence the name z-bus or zig-zag buses as shown in Figure A.1. Tennessee Valley Authority historically used the z-bus arrangement for its 161kV substation switchyard where three or more lines might be coming from generating stations. The two main buses are placed in the opposite sides of the 161kV switchyard to provide maximum physical separation in the Z bus arrangement. The z-bus arrangement is used "to increase system stability, for continuity of service to important loads, to maintain ties between different parts of the system with a bus out of service, to provide continuity of service in the event of the loss of main bus and to provide backup protection [1]."

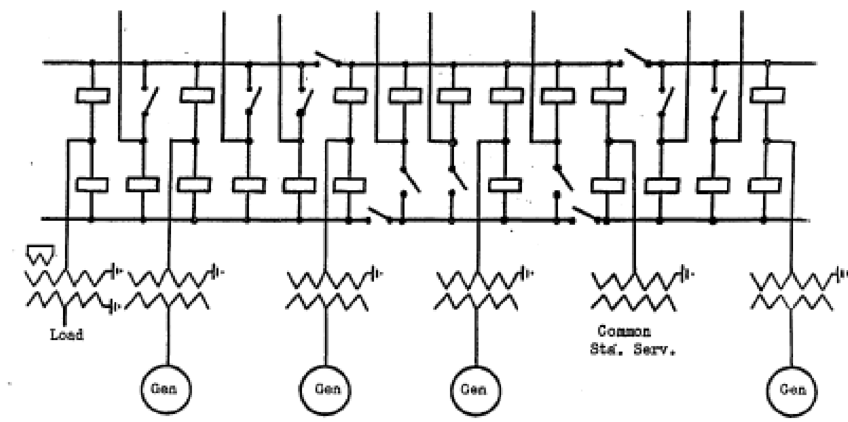

Figure A.1 Z-Bus Arrangements [1]

<u>Bus Breakup and Bus Backup, LEO total fault current, Apparent Impedance, definite time</u>

Bus breakup relays are placed where there is a load between double breakers as shown in Figure A.2. Line relay R1 should operate for a fault F1. If relay R1 fails to operate or R1 operates and breaker fails, the bus breakup relay associated with bus 1 should then operate. Bus break up relay is the backup for line 1 in the event of the failure of line relay or breaker. Bus break up relay only opens breaker 838, so there is no current contribution to fault- F1 from lines 4 and 7.

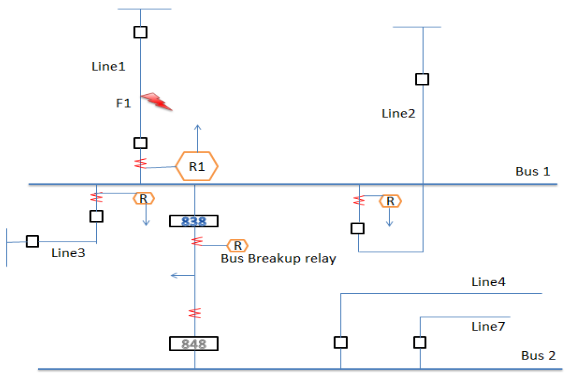

Figure A.2 Z-Bus Arrangement and Bus Breakup Relay

All breakers are tripped on bus 1 for bus back up. Bus back up relay settings is the same as bus breakup relay. The short reach and long reach settings for bus breakup relays for Norris and North Knoxville are attached in appendix. Figure A.3 shows the bus breakup relays for Norris and North Knoxville when there are no other breakers (or taps) added on the transmission line.

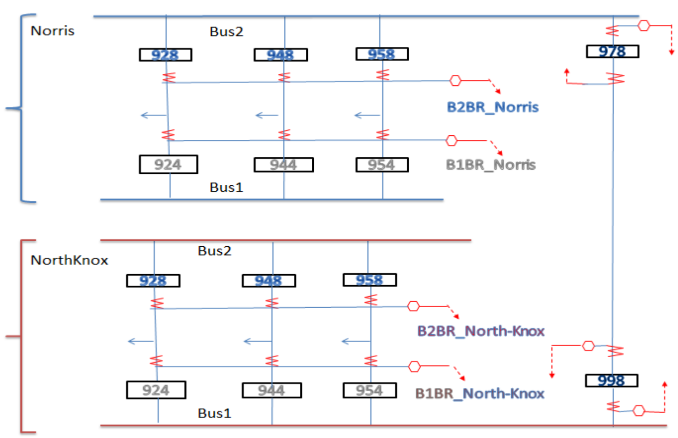

Figure A.3 Bus Breakup Relays for Norris and NorthKnox

Bus break up relay explanation and calculations

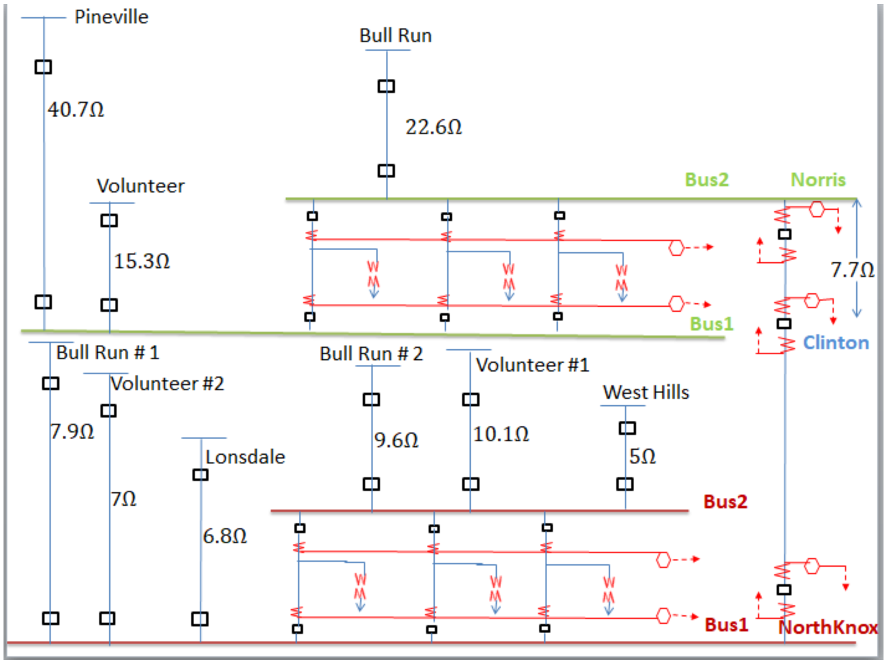

Figure A.4 Addition of Clinton Breaker

Zone 1 of line relay at North-Knoxville should operate for the close-in fault out of North-Knoxville line as shown in Figure A.4. Zone 2 of line relay at Norris can act as a backup for the fault beyond the lines connected to North-Knoxville depending on the percentage of the line impedance chosen for zone 2 of Norris line relay. If the line protection zone 1 of North-Knoxville fails to operate or the breaker fails, the bus breakup scheme at North-Knoxville (B1BR _North-Knoxville) should then operate first before the line protection zone 2 of Norris operates. Z2 time delay for Norris will be the same regardless of the fault location that is why it is called the definite time element. For a close-in fault, short reach bus breakup timer is used as shown below to set up Z2 timer for Norris and North-Knoxville.

<u>Norris terminal looking at North Knoxville</u>

$$NorthKnoxville\ Bus\ Breakup\ operation$$

$$= NorthKnoxville\ Short\ Reach\ time + LockoutRelayTime + Breaker\ Time$$

$$= 20 + 1 + 3 = \ 24 \sim$$

$$Norris\ Z2\ timer = NorthKnoxville\ Bus\ Breakup\ operation + Margin$$

$$= 24 + 15 = 39\sim\ \cong\ \text{set } 40 \sim$$

<u>North Knoxville looking at Norris</u>

$$Norris\ Bus\ Breakup\ operation$$

$$= Norris\ Short\ Reach\ time + LockoutRelayTime + Breaker\ Time$$

$$= 15 + 1 + 3 = 19 \sim$$

$$NorthKnoxville\ Z2\ timer = Norris\ Bus\ Breakup\ operation + Margin$$

$$= 19 + 15 = 34\sim\ \cong\ \text{set } 35 \sim$$

BBR short reach = 60% of the shortest Zline Impedance

BBR Long Reach=120% of the longest Zapparent

$$\text{Zapparent} = \frac{LEO\ total\ fault\ current}{Bus\ Breakup\ Current} * Zline$$

LEO= line end open (for example: North-Knox to Clinton LEO total fault current meaning: Fault at Clinton, Clinton Breaker open)

Table A.1 Bus Breakup $Z_{apparent}$

Station	Bus	Line	Impedance (ohms)	Zone 2 time delay	LEO total fault current	Bus breakup current	BB Zapp
North Knox	1	Clinton	14.2	35	5477	2380	32.7
North Knox	1	Bull Run #1	7.9	30	8388	4285	15.5
North Knox	1	Volunteer #2	7	30	8796	4700	13.1
North Knox	1	Lonsdale #1	6.8	30	9568	4427	14.7
North Knox	2	Bull Run #2	9.6	30	7330	5289	13.3
North Knox	2	Volunteer #1	10.1	30	6974	5131	13.7
North Knox	2	West Hills	5	30	11719	7619	7.7
Norris	1	Pineville	40.7	30	2014	1322	62.0
Norris	1	Volunteer	15.3	30	4071	3355	18.6
Norris	2	Bull Run	22.6	30	3193	2335	30.9
Norris	2	Clinton	7.7	40	6392	4632	10.6

<u>**Norris Bus 1 Breakup relay:**</u>

Norris to Pineville Bus 1 =40.7 Ω, Zapp = 62.0Ω

Norris to Volunteer Bus1=15.3 Ω, $\text{Zapp} = 18.6\Omega$

Short reach = $0.60 * 15.3 = 9.2\ \Omega,\ 15\sim$ (Tip: for short reach, you just use 15 ∼)

Long Reach = $1.20 * 62 = 72\ \Omega,\ 50\sim$

Tip for long reach: Take the slowest zone 2 time delay from all the lines out of Norris Bus 1, add 1∼ for LOR, 3 ∼ for breaker and 15 ∼ margin

$Long\ reach\ Norris\ Bus1\ Breakup\ relay = slowest\ zone\ 2\ time\ delay + LOR + Breaker + Margin = 30 + 1 + 3 + 15 = 49\sim$, so set it to 50∼

Norris Bus 2 Breakup relay:

Norris to BullRun = $22.6\Omega,\ \text{Zapp} = 30.9\Omega$

Norris to Clinton=7.7 Ω, $\text{Zapp} = 10.6\Omega$

Short reach = $0.60 * 7.7 = 4.6\ \Omega,\ 15\sim$

Long Reach = $1.2 * 30.9 = 37.1\ \Omega,\ 60\sim$

$$
\begin{aligned}
&Long\ Reach\ Norris\ Bus2\ Breakup\ relay \\
&\quad = slowest\ zone\ 2\ time\ delay + LOR + Breaker + Margin \\
&\quad = 40 + 1 + 3 + 15 = 59\sim, \text{ so set it to } 60\sim
\end{aligned}
$$

North-Knoxville Bus 1 Breakup relay:

North-Knox to Lonsdale#1 = 6.8 Ω, $\text{Zapp} = 14.7\Omega$

North-Knox to Clinton=14.2 Ω, $\text{Zapp} = 32.7\Omega$

Short reach = $0.60 * 6.8 = 4.1\ \Omega,\ 15\sim$

Long Reach = $1.2 * 32.7 = 39.2\ \Omega,\ 55\sim$

$$
\begin{aligned}
&Long\ Reach\ North - Knox\ Bus1\ Breakup\ relay \\
&\quad = slowest\ zone\ 2\ time\ delay + LOR + Breaker + Margin \\
&\quad = 35 + 1 + 3 + 15 = 54\sim, \text{ so set it to } 55\sim
\end{aligned}
$$

North-Knoxville Bus 2 Breakup relay:

North-Knox to West Hills = 5 Ω, Zapp = 7.7Ω

North-Knox to Volunteer#1=10.1 Ω, Zapp = 13.7Ω

Short reach = $0.60 * 5 = 3\ \Omega,\ 15 \sim$

Long Reach = $1.2 * 13.7 = 16.4\ \Omega,\ 50 \sim$

$$Long\ Reach\ North - Knox\ Bus2\ Breakup\ relay$$

$$= slowest\ zone\ 2\ time\ delay + LOR + Breaker + Margin$$

$$= 30 + 1 + 3 + 15 = 49 \sim,\ \text{so set it to } 50\sim$$

Zone distance element settings with addition of multiple breakers

Norris looking toward North Knoxville: $\boldsymbol{Zone1 = 0.80 \times Z_{Line}}$; $\boldsymbol{Zone2 = 1.30 \times Z_{Line}}$

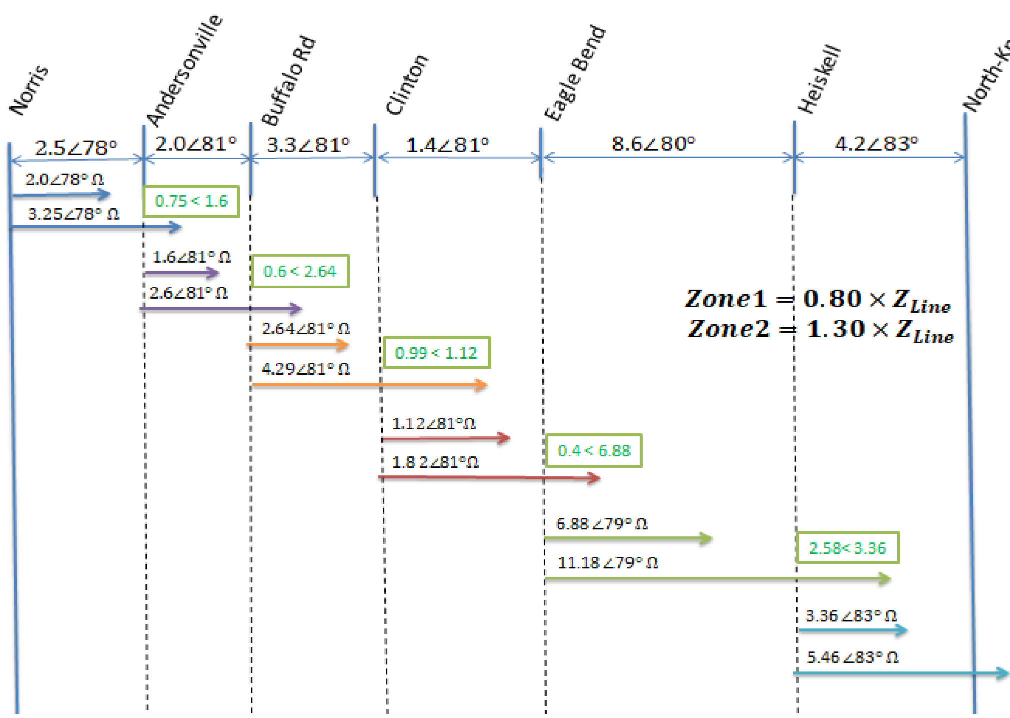

Figure A.5 Zone 2 Set to 130% of Zline

Explanation of Z2 timer

Heiskell to North Knox
Heiskell coordinates with North-Knox short reach bus breakup timer.
North-Knoxville short reach bus breakup = short reach +LOR + breaker= 20+1+3=24∼
So Z2 Heiskell = 24+15 (margin) = 39, so set it 40∼

Eagle Bend to Heiskell
Eagle Bend Z2= 11.18 Ω , Eagle Bend to Heiskell=8.6 Ω
Eagle Bend Z2 past Heiskell=11.18 Ω -8.6 Ω=2.58 Ω < 3.36 Ω , Heiskell-NorthKnox, Z1 setting
Therefore Eagle Bend Z2 coordinates with Heiskell Z1+ Heiskell BF timer
Total clearing time for Heiskell Z1 fault = Heiskell Z1+ Heiskell BF timer=1+15=16∼
Eagle Bend Z2 time delay= 16+15 =31 so set 35∼

Clinton to Eagle Bend
Clinton Z2=1.82 Ω, Clinton to Eagle Bend =1.4 Ω
Clinton Z2 past spider =1.82-1.4=0.42 Ω<6.88 Ω, Eagle Bend-Heiskell Z1 setting
Eagle Bend Z1 fault clearing time= Eagle Bend Z1+ Eagle Bend BF timer= 1+15=16∼
Clinton Z2 coordinates with Z1 timer Eagle Bend -Heiskell+ margin
Clinton Z2= 16+15=31 so set 35∼

Buffalo Rd to Clinton
Z2Buffalo Rd =4.29Ω, BuffloRd-Clinton=3.3 Ω
Z2 Buffalo Rd past Clinton =0.99 Ω<1.12, Z1 of Clinton-Eagle Bend
Therefore Buffalo Rd Z2 coordinates with Clinton Z1+Clinton BF timer =1+15=16∼
Buffalo Rd Z2=16+15=31≌ 35∼

Andersonville to Buffalo Rd
Z2 Andersonville =2.6 Ω, Andersonville-Buffalo Rd=2.0 Ω
Z2 Andersonville past Buffalo Rd =0.6 Ω<2.64, Z1 of Buffalo Rd-Clinton
Therefore Andersonville Z2 coordinates with Buffalo Rd Z1+ Buffalo Rd BF timer
Buffalo Rd Z1 fault Clearing time = Buffalo Rd Z1+ Buffalo Rd BF timer =1+15=16∼
Andersonville Z2 =16+15=31≌ 35∼

Norris to Andersonville
Norris Z2=3.25 Ω, Norris- Andersonville=2.5 Ω
Norris Z2 past Andersonville =0.75 Ω<1.6 Ω, Z1 of Andersonville-Buffalo Rd
Therefore Norris Z2 coordinates with Andersonville Z1+ Andersonville BF timer
Andersonville Z1 fault Clearing time = Andersonville Z1+ Andersonville BF timer =1+15=16∼
Norris Z2 =16+15=31≌ 35∼

North Knoxville looking towards Norris: $\boldsymbol{Zone1 = 0.80 \times Z_{Line}}$; $\boldsymbol{Zone2 = 1.30 \times Z_{Line}}$

Andersonville to Norris
Z2 Andersonville coordinates with Norris short reach bus breakup timer.
Norris short reach bus breakup = short reach +LOR + breaker= 15+1+3=19∼
Andersonville Z2= 19+15 (margin) = 34, so set it 35∼

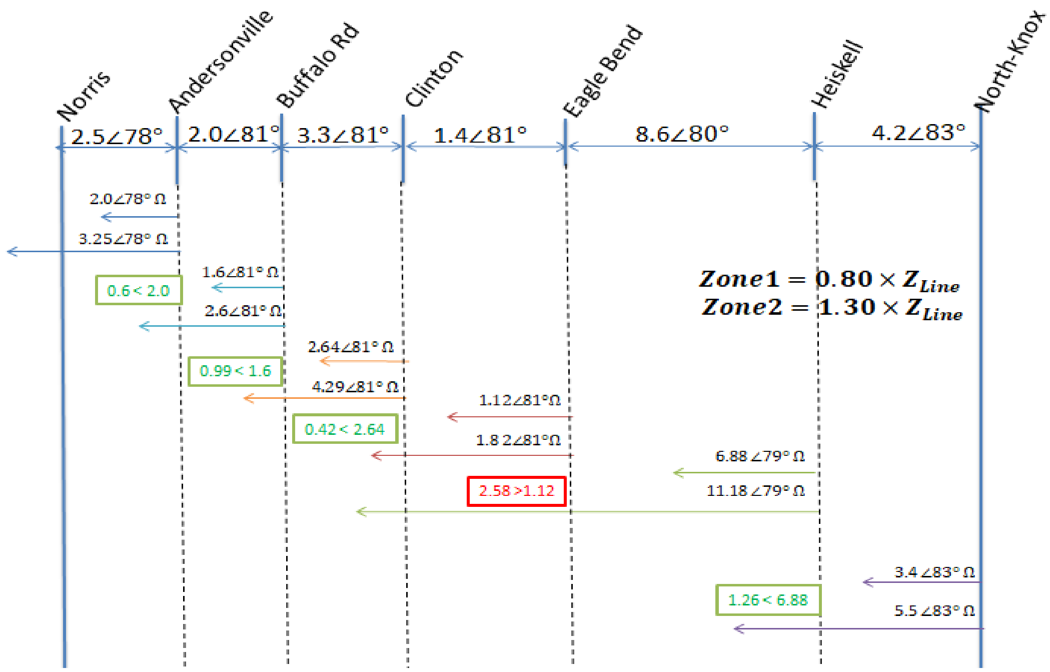

Figure A.6 Zone 2 Set to 130% of Zline

Buffalo Rd to Andersonville

Z2 Buffalo Rd =2.6 Ω, Andersonville-Buffalo Rd=2.0 Ω
Z2 Buffalo Rd past Andersonville =0.6 Ω < 2.0, Z1 of Andersonville- Norris
Therefore Buffalo Rd Z2 coordinates with Andersonville Z1+ Andersonville BF timer
Andersonville Z1 fault Clearing time= Andersonville Z1+ Andersonville BF timer =1+15=16~
Buffalo Rd Z2 =16+15=31≌ 35~

Clinton to Buffalo Rd

Z2 Clinton =4.29Ω, BuffloRd-Clinton=3.3 Ω
Z2 Clinton past Buffalo Rd= 0.99 Ω < 1.6, Z1 of Buffalo Rd- Andersonville
Therefore Clinton Z2 coordinates with Buffalo Rd Z1+ Buffalo Rd BF timer =1+15=16~
Clinton Z2=16+15=31≌ 35~

Eagle Bend to Clinton

Eagle Bend Z2=1.82 Ω, Clinton to Eagle Bend =1.4 Ω
Eagle Bend Z2 past Clinton =1.82-1.4=0.42 Ω < 2.64 Ω, Clinton- Buffalo Rd Z1 setting
Eagle Bend Z2 coordinates with Clinton Z1+ Clinton BF timer
Clinton Z1 fault clearing time= Clinton Z1+ Clinton BF timer= 1+15=16~
Eagle Bend Z2= 16+15=31 so set 35~

Heiskell to Eagle Bend

Heiskell Z2= 11.18 Ω , Eagle Bend to Heiskell=8.6 Ω
Heiskell Z2 past Eagle Bend =11.18 Ω -8.6 Ω=2.58 Ω > 1.12 Ω , Eagle Bend - Clinton, Z1 setting
Therefore Heiskell Z2 coordinates with Eagle Bend Z2+ Eagle Bend BF timer + margin
Heiskell Z2 time delay= 35+15+15 =65 so set 65~

North Knoxville to Heiskell

North Knoxville Z2=5.46 Ω , North Knoxville to Heiskell =4.2 Ω
North Knoxville Z2 past Heiskell=5.46-4.2=1.26 < 6.88, Z1 setting of Heiskell to Eagle Bend
Therefore North Knoxville coordinates with Heiskell Z1+ Heiskell BF timer=1+15=16~
North Knoxville Z2 = 16+15 (margin) = 34, so set it 35~

North Knoxville looking towards Norris: $Zone1 = 0.80 \times Z_{Line}$; $Zone2 = 1.20 \times Z_{Line}$

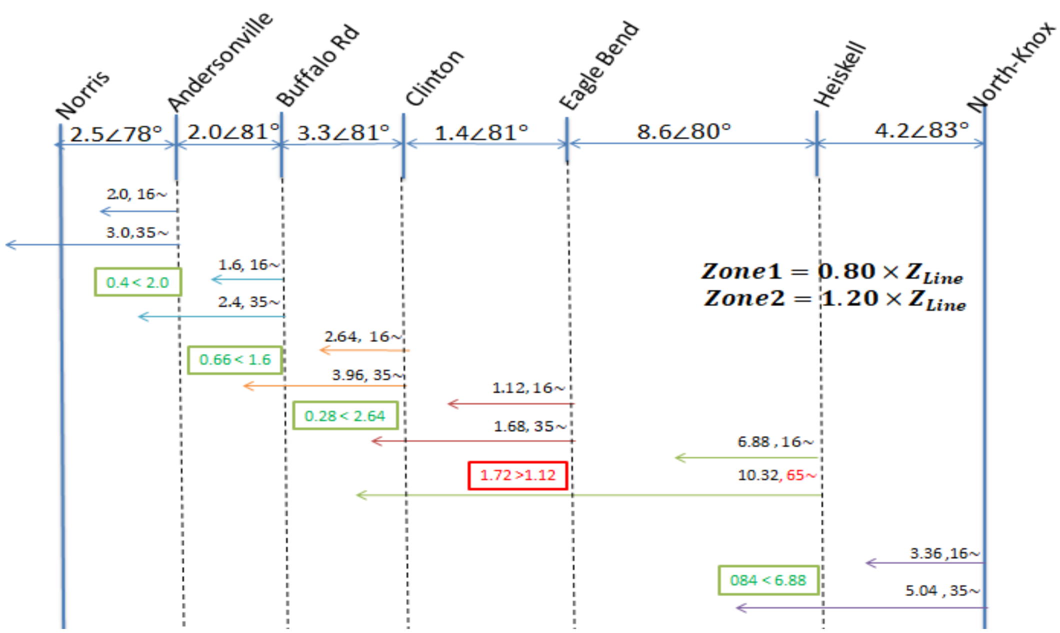

Figure A.7 Zone 2 Set to 120% of Zline

Andersonville to Norris

Z2 Andersonville coordinates with Norris short reach bus breakup timer.
Norris short reach bus breakup = short reach +LOR + breaker= 15+1+3=19~
Andersonville Z2= 19+15 (margin) = 34, so set it 35~

Buffalo Rd to Andersonville

Z2 Buffalo Rd =2.4 Ω, Andersonville-Buffalo Rd=2.0 Ω
Z2 Buffalo Rd past Andersonville =0.4 Ω < 2.0, Z1 of Andersonville- Norris
Therefore Buffalo Rd Z2 coordinates with Andersonville Z1+ Andersonville BF timer
Andersonville Z1 fault Clearing time= Andersonville Z1+ Andersonville BF timer =1+15=16~
Buffalo Rd Z2 =16+15=31≅ 35~

Clinton to Buffalo Rd

Z2 Clinton =3.96 Ω, Bufflo Rd-Clinton=3.3 Ω
Z2 Clinton past Buffalo Rd= 0.66 Ω < 1.6, Z1 of Buffalo Rd- Andersonville
Therefore Clinton Z2 coordinates with Buffalo Rd Z1+ Buffalo Rd BF timer =1+15=16~

Clinton Z2=16+15=31≅ 35~

Eagle Bend to Clinton

Eagle Bend Z2=1.68 Ω, Clinton to Eagle Bend =1.4 Ω
Eagle Bend Z2 past Clinton =1.68-1.4=0.28 Ω < 2.64 Ω, Clinton- Buffalo Rd Z1 setting
Eagle Bend Z2 coordinates with Clinton Z1+ Clinton BF timer
Clinton Z1 fault clearing time= Clinton Z1+ Clinton BF timer= 1+15=16~
Eagle Bend Z2= 16+15=31 so set 35~

Heiskell to Eagle Bend

Heiskell Z2= 10.32 Ω , Eagle Bend to Heiskell=8.6 Ω
Heiskell Z2 past Eagle Bend =10.32 Ω -8.6 Ω=1.72 Ω > 1.12 Ω , Eagle Bend- Clinton, Z1 setting
Therefore Heiskell Z2 coordinates with Eagle Bend Z2+ Eagle Bend BF timer + margin
Heiskell Z2 time delay= 35+15+15 =65 so set 65~

North Knoxville to Heiskell

North Knoxville Z2=5.04 Ω , North Knoxville to Heiskell =4.2 Ω
North Knoxville Z2 past Heiskell=5.04-4.2=0.84<6.88, Z1 setting of Heiskell to Eagle Bend
Therefore North Knoxville coordinates with Heiskell Z1+ Heiskell BF timer=1+15=16~
North Knoxville Z2 = 16+15 (margin) = 34, so set it 35~

Norris looking toward North Knoxville: $\boldsymbol{Zone1 = 0.80 \times Z_{Line}}$; $\boldsymbol{Zone2 = 1.40 \times Z_{Line}}$

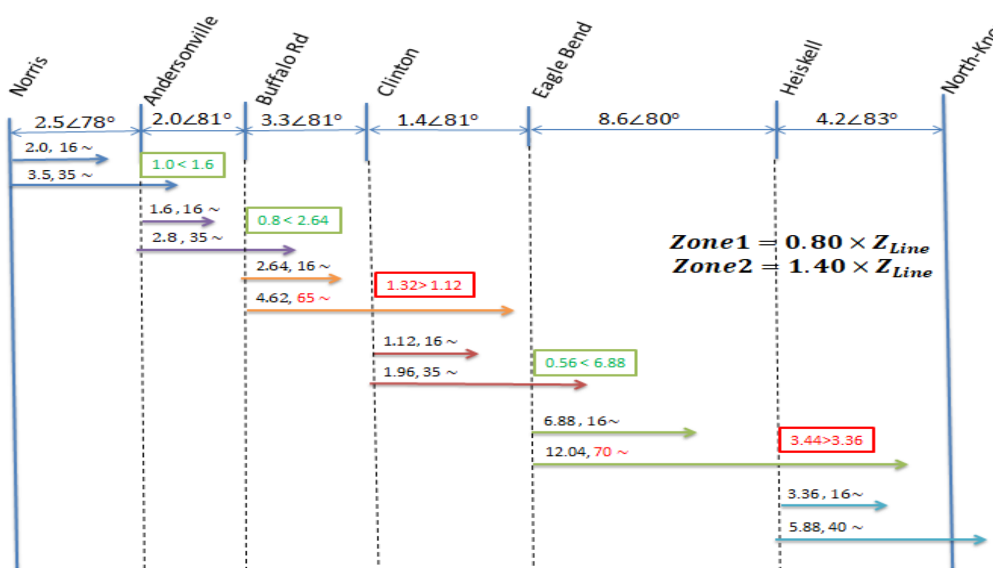

Figure A.8 Zone 2 Set to 140% of Zline

Heiskell to North Knox

Heiskell coordinates with North-Knoxville short reach bus breakup timer.
North-Knoxville short reach bus breakup = short reach +LOR + breaker= 20+1+3=24~

Heiskell Z2 time delay= 24+15 (margin) = 39, so set it 40~

Eagle Bend to Heiskell

Eagle Bend Z2= 12.04 Ω , Eagle Bend to Heiskell=8.6 Ω
Eagle Bend Z2 past Heiskell=12.04 Ω -8.6 Ω=3.44 Ω > 3.36 Ω , Heiskell-NorthKnox, Z1 setting
Therefore Eagle Bend Z2 coordinates with Heiskell Z2+ Heiskell BF timer + Margin
Total clearing time for Heiskell Z1 fault = Heiskell Z1+ Heiskell BF timer=1+15=16~
Eagle Bend Z2 time delay= 40+15+15 =70~

Clinton to Eagle Bend

Clinton Z2=1.96 Ω, Clinton to Eagle Bend =1.4 Ω
Clinton Z2 past spider =1.96-1.4=0.56 Ω<6.88 Ω, Eagle Bend-Heiskell Z1 setting
Eagle Bend Z1 fault clearing time= Eagle Bend Z1+ Eagle Bend BF timer= 1+15=16~
Clinton Z2 coordinates with Eagle Bend Z1 fault clearing time+ margin
Clinton Z2= 16+15=31 so set 35~

Buffalo Rd to Clinton

Z2Buffalo Rd =4.62 Ω, BuffloRd-Clinton=3.3 Ω
Z2 Buffalo Rd past Clinton =1.32 Ω>1.12Ω, Z1 of Clinton-Eagle Bend
Therefore Buffalo Rd Z2 coordinates with Clinton Z2+Clinton BF timer + Margin
Buffalo Rd Z2=35+15+15=65~

Andersonville to Buffalo Rd

Z2 Andersonville =2.8 Ω, Andersonville-Buffalo Rd=2.0 Ω
Z2 Andersonville past Buffalo Rd =0.8 Ω<2.64Ω, Z1 of Buffalo Rd-Clinton
Therefore Andersonville Z2 coordinates with Buffalo Rd Z1+ Buffalo Rd BF timer
Buffalo Rd Z1 fault Clearing time = Buffalo Rd Z1+ Buffalo Rd BF timer =1+15=16~
Andersonville Z2 =16+15=31≌ 35~

Norris to Andersonville

Norris Z2=3.5 Ω, Norris- Andersonville=2.5 Ω
Norris Z2 past Andersonville =1.0 Ω<1.6 Ω, Z1 of Andersonville-Buffalo Rd
Therefore Norris Z2 coordinates with Andersonville Z1+ Andersonville BF timer
Andersonville Z1 fault Clearing time = Andersonville Z1+ Andersonville BF timer =1+15=16~
Norris Z2 =16+15=31≌ 35~

Norris looking toward North Knoxville: $\boldsymbol{Zone1 = 0.80 \times Z_{Line}}$; $\boldsymbol{Zone2 = 1.50 \times Z_{Line}}$

Heiskell to North Knox

Heiskell coordinates with North-Knoxville short reach bus breakup timer.
North-Knoxville short reach bus breakup = short reach +LOR + breaker= 20+1+3=24~
Heiskell Z2 time delay= 24+15 (margin) = 39, so set it 40~

Eagle Bend to Heiskell

Eagle Bend Z2= 12.90 Ω , Eagle Bend to Heiskell=8.6 Ω
Eagle Bend Z2 past Heiskell=12.90 Ω -8.6 Ω=4.3 Ω > 3.36 Ω , Heiskell-NorthKnox, Z1 setting
Therefore Eagle Bend Z2 coordinates with Heiskell Z2+ Heiskell BF timer + Margin
Total clearing time for Heiskell Z1 fault = Heiskell Z1+ Heiskell BF timer=1+15=16~
Eagle Bend Z2 time delay= 40+15+15 =70~

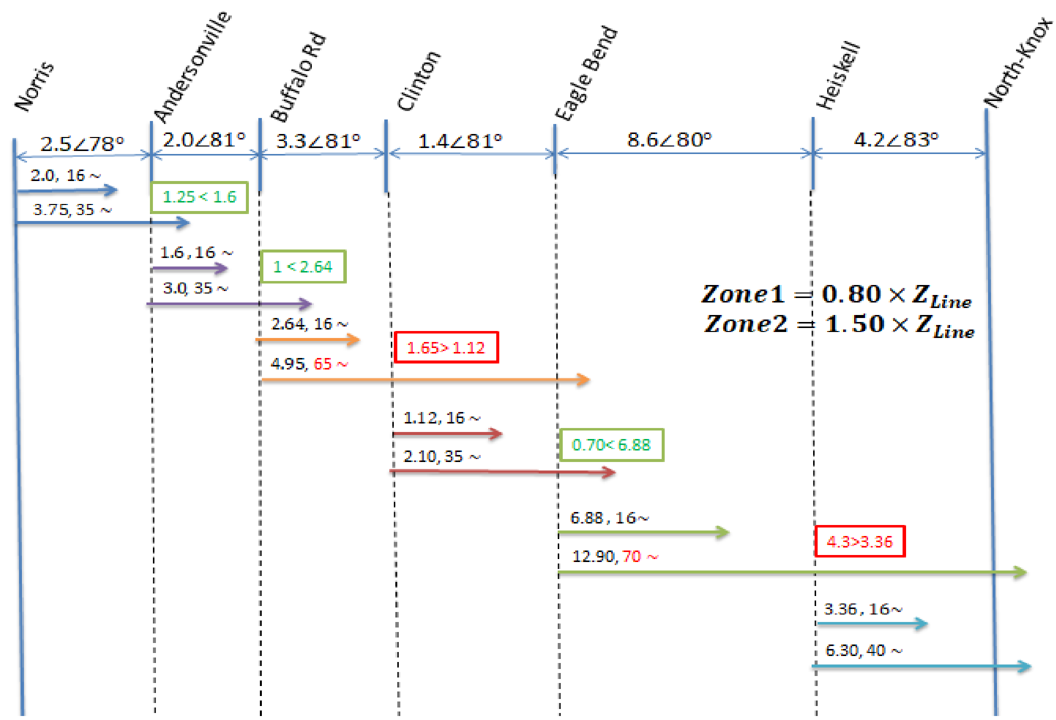

Figure A.9 Zone 2 Set to 150% of Zline

Clinton to Eagle Bend

Clinton Z2=2.1 Ω, Clinton to Eagle Bend =1.4 Ω
Clinton Z2 past spider =2.1-1.4=0.7 Ω<6.88 Ω, Eagle Bend-Heiskell Z1 setting
Eagle Bend Z1 fault clearing time= Eagle Bend Z1+ Eagle Bend BF timer= 1+15=16~
Clinton Z2 coordinates with Eagle Bend Z1 fault clearing time+ margin
Clinton Z2= 16+15=31 so set 35~

Buffalo Rd to Clinton

Z2Buffalo Rd =4.95 Ω, BuffloRd-Clinton=3.3 Ω
Z2 Buffalo Rd past Clinton =1.65 Ω>1.12Ω, Z1 of Clinton-Eagle Bend
Therefore Buffalo Rd Z2 coordinates with Clinton Z2+Clinton BF timer + Margin
Buffalo Rd Z2=35+15+15=65~

Andersonville to Buffalo Rd

Z2 Andersonville =3.0 Ω, Andersonville-Buffalo Rd=2.0 Ω
Z2 Andersonville past Buffalo Rd =1.0 Ω<2.64Ω, Z1 of Buffalo Rd-Clinton
Therefore Andersonville Z2 coordinates with Buffalo Rd Z1+ Buffalo Rd BF timer
Buffalo Rd Z1 fault Clearing time = Buffalo Rd Z1+ Buffalo Rd BF timer =1+15=16~
Andersonville Z2 =16+15=31≅ 35~

Norris to Andersonville

Norris Z2=3.75 Ω, Norris- Andersonville=2.5 Ω
Norris Z2 past Andersonville =1.25 Ω<1.6 Ω, Z1 of Andersonville-Buffalo Rd

Therefore Norris Z2 coordinates with Andersonville Z1+ Andersonville BF timer
Andersonville Z1 fault Clearing time = Andersonville Z1+ Andersonville BF timer =1+15=16~
Norris Z2 =16+15=31≌ 35~

51N settings, 3I0, Tp, Time dial calculation sample

Calculating 3I0 from Clinton relay when single phase to ground fault is applied at Eagle Bend

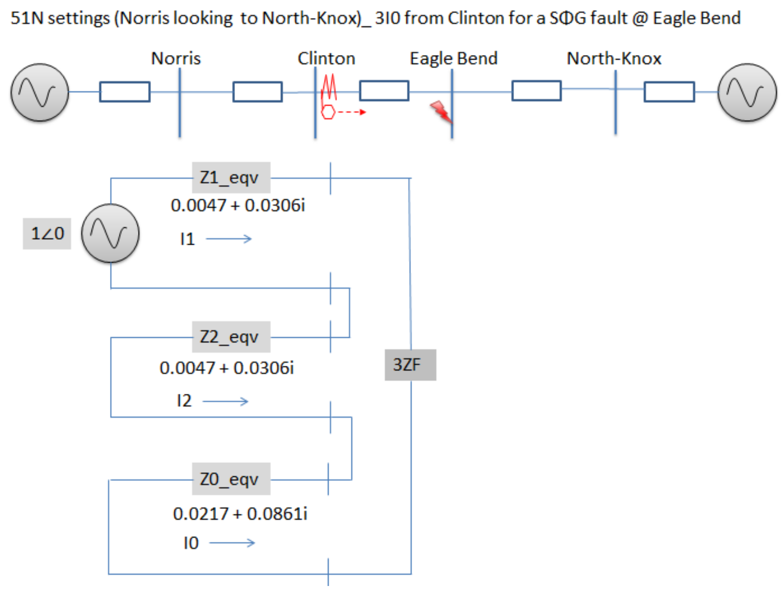

Figure A.10 Relay at Clinton when Single Phase to Ground Fault Applied at Eagle Bend

Matlab Script and Output

```
%51N_Norris looking to NorthKnox
%3I0 from Clinton fault @ EagleBend Bus
VLL=161000; VLN=VLL/(sqrt(3));CT_ratio=240/1;VT_ratio=1400/1;Sbase=100*10^6;
a=-0.5+0.866025*j;a_square=-0.5-0.866025*j;
A=[1 1 1;1 a_square a;1 a a_square];
% Bolted means ZF=0 ohm
ZF=0;
%Source impedances_@ Norris and @North-Knoxville
%Norris ATC:Z+ = 0.00411 + j0.02679 pu, Z0 = 0.01436 + j0.07506
%North Knox ATC:Z+ = 0.00110 + j0.01219 pu, Z0 = 0.00287 + j0.01731
ZSplus_Norris=0.00411 + j*0.02679;Zszero_Norris= 0.01436 + j*0.07506;
ZSplus_NorthKnox=0.00110 + j*0.01219;Zszero_NorthKnox=0.00287 + j*0.01731;
%Norris_Clinton
ZplusNorris_Clinton=0.0019+j*0.0125+0.0012+j*0.0076+0.0020+j*0.0093;
Z0_Norris_Clinton=0.0100+j*0.0342+0.0059+j*0.0199+0.0084+j*0.0257;
```

```
%Clinton_EagleBend
Zplus_Clinton_EagleBend= 0.0008+j*0.0052;
Z0_Clinton_EagleBend=0.0040+j*0.0142;
%Heiskell_NorthKnox
Zplus_Heiskell_NorthKnox=0.0020+j*0.016;
Z0_Heiskell_NorthKnox=0.0113+j*0.0477;
%HeiskellTap_Heiskell
Zplus_HeiskellTap_Heiskell=0.0001+j*0.0005;
Z0_HeiskellTap_Heiskell=0.0004+j*0.0016;
%EagleBendTap_HeiskellTap
Zplus_EagleBendTap_HeiskellTap=0.0035+j*0.0176;
Z0_EagleBendTap_HeiskellTap=0.0167+j*0.0555;
%EagleBendTap_EagleBend
Zplus_EagleBendTap_EagleBend=0.0022+0.0147*j;
Z0_EagleBendTap_EagleBend=0.0130+0.0535*j;
%EagleBend_NorthKnox
Zplus_EagleBend_NorthKnox=Zplus_Heiskell_NorthKnox+Zplus_HeiskellTap_Heiskell+Zplus_EagleB
endTap_HeiskellTap+Zplus_EagleBendTap_EagleBend;
Z0_EagleBend_NorthKnox=Z0_Heiskell_NorthKnox+Z0_HeiskellTap_Heiskell+Z0_EagleBendTap_He
iskellTap+Z0_EagleBendTap_EagleBend;
%Z_equivalent and sequence currents
Zplus_Eqv=
((ZSplus_Norris+ZplusNorris_Clinton+Zplus_Clinton_EagleBend)*(Zplus_EagleBend_NorthKnox+ZSp
lus_NorthKnox))/(ZSplus_Norris+ZplusNorris_Clinton+Zplus_Clinton_EagleBend+Zplus_EagleBend_N
orthKnox+ZSplus_NorthKnox)
Zminus_Eqv=Zplus_Eqv
Zzero_Eqv=((Zszero_Norris+Z0_Norris_Clinton+Z0_Clinton_EagleBend)*(Z0_EagleBend_NorthKnox+
Zszero_NorthKnox))/(Zszero_Norris+Z0_Norris_Clinton+Z0_Clinton_EagleBend+Z0_EagleBend_North
Knox+Zszero_NorthKnox)
%Sequence currents for Equivalent network
I1=(1+0*j)/(Zplus_Eqv+Zminus_Eqv+Zzero_Eqv+3*ZF);
I2=I1;I0=I1;
I_sequence=[I0;I1;I2]
I_phase_amps=A*I_sequence*(Sbase/(sqrt(3)*VLL))
Iphase_mag_Angle=round([abs(I_phase_amps) radtodeg(angle(I_phase_amps))])
Total3I0_Amps=(3*I0)*((Sbase/(sqrt(3)*VLL)))
Total3I0_amps_angle=round([abs(Total3I0_Amps) radtodeg(angle(Total3I0_Amps))])
%sequence currents at relay location
I1_relay=((Zplus_EagleBend_NorthKnox+ZSplus_NorthKnox)*I1)/(ZSplus_Norris+ZplusNorris_Clinto
n+Zplus_Clinton_EagleBend+Zplus_EagleBend_NorthKnox+ZSplus_NorthKnox);
I2_relay=I1_relay;
I0_relay=((Z0_EagleBend_NorthKnox+Zszero_NorthKnox)*I0)/(Zszero_Norris+Z0_Norris_Clinton+Z0
_Clinton_EagleBend+Z0_EagleBend_NorthKnox+Zszero_NorthKnox);
I_sequence_relay=[I0_relay;I1_relay;I2_relay]
Iphase_relay_pu=A*I_sequence_relay
Iphase_relay_mag_angle_pu=[abs(Iphase_relay_pu) radtodeg(angle(Iphase_relay_pu))]
Iphase_relay_mag_angle_Amps=round([abs(Iphase_relay_pu)*((Sbase/(sqrt(3)*VLL)))
radtodeg(angle(Iphase_relay_pu))])
%51Npickup = 10% of the remote bus ground fault
ThreeI0_Amps=(3*I0_relay)*((Sbase/(sqrt(3)*VLL)))
```

```
ThreeI0_amps_angle=round([abs(ThreeI0_Amps) radtodeg(angle(ThreeI0_Amps))])
Fifty1Npickup_Aprimary=round(abs(ThreeI0_Amps)*(10/100))
Fifty1Npickup_Asecondary=Fifty1Npickup_Aprimary/CT_ratio
%Calculate Time Dial or time lever using following equation
%Tp=Td *(0.0963+(3.88/(M^2-1)))*60 where Tp=35 cycles and M=3I0/pickup =10
Tp=35;
M=round(abs(ThreeI0_Amps)/Fifty1Npickup_Aprimary);
Td_Norris= round((Tp/60)/((0.0963+(3.88/(M^2-1))))*10)/10
```

51N settings, 3I0, Tp, Time dial calculation sample

OUTPUT

```
>> RelayAtClintonFaultAtEagleBend_51N_Norris2NK
Zplus_Eqv =   0.0047 + 0.0306i
Zminus_Eqv =   0.0047 + 0.0306i
Zzero_Eqv =   0.0217 + 0.0861i

I_sequence =
   1.3747 - 6.4966i
   1.3747 - 6.4966i
   1.3747 - 6.4966i

I_phase_amps =
   1.0e+03 *
   1.4789 - 6.9891i
  -0.0000 + 0.0000i
   0.0000 - 0.0000i

Iphase_mag_Angle =
        7144         -78
           0         170
           0         -10

Total3I0_Amps =   1.4789e+03 - 6.9891e+03i

Total3I0_amps_angle =        7144         -78

I_sequence_relay =
   0.7008 - 3.3098i
   0.7114 - 3.2277i
   0.7114 - 3.2277i

Iphase_relay_pu =
   2.1236 - 9.7653i
  -0.0106 - 0.0821i
  -0.0106 - 0.0821i

Iphase_relay_mag_angle_pu =
    9.9935  -77.7315
    0.0828  -97.3709
```

0.0828 -97.3709
Iphase_relay_mag_angle_Amps =
3584 -78
30 -97
30 -97
ThreeI0_Amps = 7.5389e+02 - 3.5608e+03i

ThreeI0_amps_angle = 3640 -78

Fifty1Npickup_Aprimary = 364

Fifty1Npickup_Asecondary = 1.5167

Td_Norris = 4.3000

VITA

Mugdha Alverson was born in Sarbhon located in Gujarat, India, to the parents of Mayur and Daxa Desai. She is the eldest of the two kids. Mugdha finished high school and two years of college in India before she moved to the United States of America in December of 1995. She earned her Bachelor of Science in engineering degree from the University of Tennessee at Chattanooga in 2003. She got married to David Alverson and moved to Lexington KY after her graduation. She worked at Lexmark International for several years in Lexington, KY and welcomed their only child in 2010. She worked for Cirrus Logic for a short period of time after moving to Tucson, AZ. Her family moved back to Chattanooga TN in 2012 and she started pursuing her Master's degree in 2013. Mugdha graduated with Master of Science degree in Electrical Engineering in May 2019.